Multi-Variable Parametric Cost Model for Space Telescopes

H. Philip Stahl

NASA MSFC, Huntsville, AL 35821;

Todd Hendrichs

Middle Tennessee State University;

Alexander Luedtke

Brown University;

Miranda West

University of Texas at Austin;

Agenda

- Introduction and Summary
- Data Collection Methodology
- Statistical Analysis Methodology
- What to Model?: OTA or Total Mission Cost
- Single Variable Modes: Mass and Diameter
- Multi-Variable Models
- Total Mission Cost Models
- Conclusions

Agenda

- Introduction and Summary
- Motivation: 2000 NGST (JWST) Study
- Historical Models
- Data Collection Methodology
- Statistical Analysis Methodology
- What to Model?: OTA or Total Mission Cost
- Single Variable Modes: Mass and Diameter
- Multi-Variable Models
- Total Mission Cost Models
- Conclusions

Parametric Cost Models

Parametric cost models have several uses:

- high level mission concept design studies,
- identify major architectural cost drivers,
- allow high-level design trades,
- enable cost-benefit analysis for technology development investment, and
- provide a basis for estimating total project cost.

However

All Cost Models are Wrong!

But Some are Useful.

The Rest will get you into Trouble.

<u>DISCLAIMER</u>

Cost Models are only as good as their Data Base

This is a work in progress.

The results evolve as we add new missions to the Database, add data to or correct data in the Database.

Findings

Aperture Diameter is principle cost driver for space telescopes.

$$\textbf{OTA Cost} \sim \textbf{Diameter}^{\,1.4}$$

$$\textbf{OTA Cost} \sim \textbf{Dia}^{1.6}\ \lambda^{-0.25}$$

Larger diameter OTAs cost less per square meter of aperture.

Longer wavelength OTAs cost less.

If all parameters are held constant, adding mass reduces cost &

reducing mass increases cost.

Still examining Year of Development

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Methodology

Data accumulated on 59 engineering and programmatic variables

18 Variables studied for Cost Estimating Relationships (CERs)

Data sources :

NAFCOM (NASA/ Air Force Cost Model) database,
NICM (NASA Instrument Cost Model),
NSCKN (NASA Safety Center Knowledge Now),
RSIC (Redstone Scientific Information Center),
REDSTAR (Resource Data Storage and Retrieval System),
SICM (Scientific Instrument Cost Model),
project websites, and interviews.

Cost & Mass Definitions

Total Mission:

- Spacecraft
- Science Instruments
- Telescope

Instrument:

- Entire payload or experiment including telescope

Optical Telescope Assembly (OTA):

- Primary mirror
- Secondary (and tertiary if appropriate) mirror(s)
- Support structure
- Mechanisms (actuators, etc.), Electronics, Software, etc.
- Assembly, Integration & Test

Cost & Mass Definitions (2)

Cost includes:

- Phase A-D (design, development, integration and test)

Cost excludes:

- Pre-phase A (formulation)
- Phase E (launch/post-launch)
- Government labor costs (NASA employees: CS or support contractors)
- Government Furnished Equipment (GFE)
- Existing Contractor infrastructure which is not ‘billed’ to contract.
- These are ‘First Unit’ Costs only – no HST Servicing & there are no 2nd Systems.

Mass includes:

- Dry mass only (no propellant)

Fiscal Year 2011

All costs are inflated to fiscal year 2011 using the NASA New Start Index Inflation Calculator.

Details can be found at: http://cost.jsc.nasa.gov/inflation/nasa/inflateNASA.html

Technical Variables

Aperture Diameter
PM Focal Length
System Focal Length
Field of View
Pointing Stability
OTA Mass
Total Mass
Spectral Range Minimum
Wavelength of Diffraction Limit
Operating Temperature
Average Input Power
Data Rate
Design Life
Orbit

Programmatic Variables

- TRL (Technology Readiness Level)
- Year of Development (or Start of Development)
- Development Period
- Launch Year

Missions (8.6.11 Database)

Currently 45 missions in data base

- 33 'normal-incidence' UVOIR and Infrared telescopes
- 5 grazing incidence X-Ray
- 7 Radio/Microwave

Data for microwave, radio wave & grazing incidence X-Ray/EUV provides wavelength diversity

To date only normal-incidence UVOIR and Microwave telescopes used for cost modeling

Cost Model Missions Database (8.6.11)	
X-Ray Telescope	Infrared Telescopes
Chandra (AXAF)	CALIPSO
Einstein (HERO-2)	Herschel
EUVE	IRAS
FOXSI	ISO
HERO	JWST
	SOFIA
UV/Optical Telescopes	Spitzer (SIRTF)
Commercial #1	TRACE
Commercial #2	WIRE
Copernicus (OAO-3/PEP)	WISE
EO-1/ALI	
EUVE	
FUSE	Microwave Telescopes
GALEX	ACTS
HST	Cloud SAT
HUT	Planck
ICESat	WMAP
IUE	
Kepler	
LANDSAT-7	Radio Antenna
LRO/LROC NAC	SWAS
MO/MOC	TDRS-1
MO/MOLA	TDRS-7
MRO/HiRISE	
OAO-B/GEP	
SDO/AIA	
SOHO/EIT	
STERO/SECCHI	
UIT	
WUPPE	

Missions (8.6.11 Database)

Of 37 'normal-incidence' UVOIR and Microwave telescopes

27 are 'Free Flying'

4 are 'Attached' and

5 are 'Planetary/Other'

Additionally, some of these are Imaging and others are Spectroscopic.

We have not yet investigated the impact of this distinction, but expect spectroscopic to be lower cost.

Normal Incidence Database (8.6.11)	
Free Flying Telescope	Attached Telescopes
ACTS	HUT
CALIPSO	SOFIA
Cloud SAT	UIT
Commercial #1	WUPPE
Commercial #2	
Copernicus (OAO-3/PEP)	
EO-1/ALI	Planetary Telescopes
EUVE	LRO/LROC NAC
FUSE	MO/MOC
GALEX	MO/MOLA
Herschel	MRO/HiRISE
HST	STEREO/SECCHI
ICESat	
IRAS	
ISO	
IUE	
JWST	
Kepler	
LANDSAT-7	
OAO-B/GEP	
Planck	
SDO/AIA	
SOHO/EIT	
Spitzer (SIRTF)	
TRACE	
WIRE	
WISE	
WMAP	

Hubble Cost Knowledge

Hubble Cost Knowledge			
Cost Element	Old (FY11$)	Revised (FY11$)	Notes
Total Cost Phase A-D	**$ 4.0 B**	**$2.8 B**	**Old: NGST Cost Model Database**
Total OTA	$ 0.9 B	$ 0.9 B	
OTA	$ 0.7 B	$ 0.47 B	Old: allocated too much FGS/C&DH cost to OTA (should be spacecraft costs)
Optics		*$ 0.07 B*	New: REDSTAR 121-4742
Optics Control		*$ 0.08 B*	
Optical Structure		*$ 0.08 B*	
Electrical Power		*$ 0.02 B*	
Structures, mechanisms, support equipment		*$ 0.05 B*	
System Level 53%		*$ 0.14 B*	
ST Level 53%		*$ 0.01 B*	
FGS	$ 0.2	$ 0.26 B	New: REDSTAR 121-4742
C&DH		$ 0.08 B	New: REDSTAR 121-4742
Thermal Control		$ 0.01 B	New: REDSTAR 121-4742
System Level 47%		$ 0.12 B	New: REDSTAR 121-4742
ST Level 47%		$ 0.01 B	New: REDSTAR 121-4742
Total SSM		$1.14 B	New: REDSTAR 121-4742
Science Instruments		$0.5 B	New: REDSTAR 123-1064 (page 108)
ESA Contribution		$0.25 B	New: REDSTAR 123-1064 (page 108)
Total Cost Phase A-E	**$ 5.1 B**	**$ 4.6 B**	**Old: NGST Cost Model Database**
Launch		$0.62 B	New: REDSTAR 123-1064 (page 108)
Phase E		$ 1.2 B	New: REDSTAR 123-1064 (Page 108 & 122)

Note: Totals may not tie due to rounding

Missions (8.6.11 Database)

For some have only Mission data and for others have both OTA and Mission data.

We have OTA Cost:

& Diameter data for 15

& Mass data for 13

Cost Model Variables for Free Flying UVO/IR Systems (rev. 11.6.10)	
Parameter	% of data
Total Cost	89%
OTA Cost	46%
Total Cost & OTA Cost	68%
Aperture Diameter	100%
PM F Len.	71%
System F Len.	89%
FOV	86%
Pointing Stability	39%
Total Mass	93%
OTA Mass	86%
Spectral Range minimum	96%
Diffraction Limited Wavelength	61%
Operating Temperature	93%
Avg. Input Power	89%
Data Rate	79%
Design Life	96%
TRL	32%
Year of Dev.	93%
Dev. Period	89%
Date of Launch	96%
Orbit	82%
Average	78%

Missions (8.6.11 Database)

These are the missions used in our cost model analysis

15 are 'Free Flying'

4 is 'Attached' and

1 is 'Planetary'

Of theses 8 are spectroscopic or non-imaging.

Normal Incidence Database (8.6.11)	
Free Flying Telescope	Attached Telescopes
Cloud SAT	HUT
Commercial #1	SOFIA
Commercial #2	UIT
Copernicus (OAO-3/PEP)	WUPPE
GALEX	
Herschel	
HST	Planetary Telescopes
IRAS	MRO/HiRISE
JWST	
Kepler	
OAO-B/GEP	
Planck	
Spitzer (SIRTF)	
WIRE	
WISE	

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Model Creation

Start with Correlation Matrix.

Look for Variables which are Highly Correlated with Cost.

- The higher the correlation the greater the Cost Variation which is explained by a given Variable.
- Sign of correlation is important and must be consistent with Engineering Judgment.

Important for Multi-Variable Models:

- We want Variables which Independently effect Cost.
- When Variables 'cross-talk' with each other it is called Multi-Collinearity.
- Thus, avoid Variables which are highly correlated with each other.

Goodness of Correlation, Fits and Regressions

'Correlation' between variables and 'Goodness' of single variable models is evaluated via Pearson's r^2 standard percent error (SPE), and Student's T-Test p-value.

'Goodness' of multivariable fits are evaluated via Pearson's Adjusted r^2 which accounts for number of data points and number of variables.

Pearson's r^2 coefficient describes the percentage of agreement between the fitted values and the actual data.

The closer r^2 is to 1, the better the fit.

SPE is a normalized standard deviation of the fit residual (difference between data and fit) to the fit.

The closer SPE is to 0, the better the fit

Significance

The final issue is whether or not a correlation or fit is significant.

p-value is the probability that the fit or correlation would occur if the variables are independent of each other.

- The closer p-value is to 0, the more significant the fit or correlation.
- The closer p-value is to 1, the less significant.
- If the p-value for a given variable is small, then removing it from the model would cause a large change to the model.
- If p-value is large, then removing the variable will have a negligible effect

It is only possible to 'test' if the correlation between two variables is significant.

It is not possible to 'test' if two variables are independent.

Cross-Correlation Matrix

rev. 8.1.11	Total Cost	OTA Cost	Aperture Diameter	PM F Len.	System F Len.	FOV	Pointing Stability	Total Mass	OTA Mass	Spectral Range minimum	Diff. Lim. λ	Operating Temp.	Total Avg. Input Power	Data Rate	Design Life	TRL	Year of Dev.	Dev. Period	Date of Launch	Orbit
units	(FY11$M)	(FY11$M)	(m)	(m)	(m)	(°)	(Arc-Sec / Sec)	(kg)	(kg)	(μ)	(μ)	(K)	(Watts)	(Kbps)	(months)	TRL	(year)	(months)	(year)	(km)
Total Cost	1.00	0.85	0.69	0.21	0.52	0.13	-0.72	0.68	0.85	0.21	-0.05	-0.11	0.57	0.05	0.30	-0.45	-0.15	0.70	0.03	0.46
OTA Cost		1.00	0.78	0.88	0.72	-0.13	-0.80	0.84	0.95	-0.16	-0.20	0.04	0.37	0.22	0.64	-0.61	-0.03	0.62	0.16	0.07
Aperture Diameter			1.00	0.36	0.72	-0.04	-0.71	0.59	0.84	0.51	0.46	-0.05	0.44	-0.10	0.43	-0.28	-0.08	0.45	0.05	0.05
PM F Len.				1.00	0.70	0.13	-0.77	0.69	0.89	-0.48	-0.38	0.18	0.21	0.04	0.56	-0.35	-0.11	0.41	0.11	0.00
System F Len.					1.00	-0.29	-0.47	0.61	0.70	0.02	-0.13	-0.04	0.13	-0.16	0.60	-0.38	-0.22	0.43	-0.03	0.18
FOV						1.00	-0.33	0.03	0.27	0.24	0.26	-0.12	0.10	0.19	-0.15	-0.31	0.19	-0.01	0.18	0.06
Pointing Stability							1.00	-0.62	-0.87	0.16	0.18	-0.13	-0.46	-0.03	-0.54	0.26	-0.04	-0.63	-0.24	-0.03
Total Mass								1.00	0.92	-0.10	0.10	0.01	0.39	-0.19	0.46	-0.54	-0.31	0.51	-0.16	0.24
OTA Mass									1.00	-0.22	-0.22	0.00	0.27	-0.17	0.41	-0.62	-0.04	0.69	0.18	-0.35
Spectral Range minimum										1.00	0.96	-0.24	0.16	0.10	0.06	-0.09	0.19	0.17	0.19	0.12
Diff. Lim. λ											1.00	-0.28	0.10	0.15	-0.20	0.12	0.35	0.23	0.32	0.26
Operating Temp.												1.00	0.12	-0.05	0.27	0.11	-0.06	-0.39	-0.09	-0.06
Total Avg. Input Power													1.00	0.50	0.57	0.13	0.59	0.06	0.57	0.25
Data Rate														1.00	0.14	0.63	0.72	-0.09	0.70	0.28
Design Life															1.00	-0.15	0.12	0.15	0.25	0.33
TRL																1.00	0.67	-0.17	0.64	0.32
Year of Dev.																	1.00	-0.13	0.97	0.22
Dev. Period																		1.00	0.09	0.36
Date of Launch																			1.00	0.28
Orbit																				1.00

Cross-Correlation Matrix

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units	(FY11$M)	(FY11$M)	(m)	(m)	(m)	(°)	(Arc-Sec / Sec)	(kg)	(kg)	(μ)	(μ)	(K)	(Watts)	(Kbps)	(months)	TRL	(year)	(months)	(year)	(km)
Total Cost	**1.00**	**0.85**	**0.69**	0.21	0.52	0.13	**-0.72**	**0.68**	**0.85**	0.21	-0.05	-0.11	0.57	0.05	0.30	-0.45	-0.15	**0.70**	0.03	0.46
OTA Cost		**1.00**	**0.78**	**0.88**	**0.72**	-0.13	**-0.80**	**0.84**	**0.95**	-0.16	-0.20	0.04	0.37	0.22	**0.64**	**-0.61**	-0.03	**0.62**	0.16	0.07
Aperture Diameter			**1.00**	0.36	**0.72**	-0.04	**-0.71**	0.59	**0.84**	0.51	0.46	-0.05	0.44	-0.10	0.43	-0.28	-0.08	0.45	0.05	0.05
PM F Len.				**1.00**	**0.70**	0.13	**-0.77**	**0.69**	**0.89**	-0.48	-0.38	0.18	0.21	0.04	0.56	-0.35	-0.11	0.41	0.11	0.00
System F Len.					**1.00**	-0.29	-0.47	**0.61**	**0.70**	0.02	-0.13	-0.04	0.13	-0.16	0.60	-0.38	-0.22	0.43	-0.03	0.18
FOV						**1.00**	-0.33	0.03	0.27	0.24	0.26	-0.12	0.10	0.19	-0.15	-0.31	0.19	-0.01	0.18	0.06
Pointing Stability							**1.00**	**-0.62**	**-0.87**	0.16	0.18	-0.13	-0.46	-0.03	-0.54	0.26	-0.04	**-0.63**	-0.24	-0.03
Total Mass								**1.00**	**0.92**	-0.10	0.10	0.01	0.39	-0.19	0.46	-0.54	-0.31	0.51	-0.16	0.24
OTA Mass									**1.00**	-0.22	-0.22	0.00	0.27	-0.17	0.41	**-0.62**	-0.04	**0.69**	0.18	-0.35
Spectral Range minimum										**1.00**	**0.96**	-0.24	0.16	0.10	0.06	-0.09	0.19	0.17	0.19	0.12
Diff. Lim. λ											**1.00**	-0.28	0.10	0.15	-0.20	0.12	0.35	0.23	0.32	0.26
Operating Temp.												**1.00**	0.12	-0.05	0.27	0.11	-0.06	-0.39	-0.09	-0.06
Total Avg. Input Power													**1.00**	0.50	0.57	0.13	0.59	0.06	0.57	0.25
Data Rate														**1.00**	0.14	**0.63**	**0.72**	-0.09	**0.70**	0.28
Design Life															**1.00**	-0.15	0.12	0.15	0.25	0.33
TRL																**1.00**	**0.67**	-0.17	**0.64**	0.32
Year of Dev.																	**1.00**	-0.13	**0.97**	0.22
Dev. Period																		**1.00**	0.09	0.36
Date of Launch																			**1.00**	0.28
Orbit																				**1.00**

Correlations which are at least 95% significant are **Bolded**, e.g. for 12 data points a correlation of greater than 60% is significant to better than 95%.

Cross-Correlation Matrix

rev. 8.1.11	Total Cost	OTA Cost	Aperture Diameter	PM F Len.	System F Len.	FOV	Pointing Stability	Total Mass	OTA Mass	Spectral Range minimum	Diff. Lim. λ	Operating Temp.	Total Avg. Input Power	Data Rate	Design Life	TRL	Year of Dev.	Dev. Period	Date of Launch	Orbit
units	(FY11$M)	(FY11$M)	(m)	(m)	(m)	(°)	(Arc-Sec / Sec)	(kg)	(kg)	(μ)	(μ)	(K)	(Watts)	(Kbps)	(months)	TRL	(year)	(months)	(year)	(km)
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PM F Len.																			11	0.00
System F Len.																			03	0.18
FOV																			18	0.06
Pointing Stability																			24	-0.03
Total Mass																			16	0.24
OTA Mass																			18	-0.35
Spectral Range minimum																			19	0.12
Diff. Lim. λ																			32	0.26
Operating Temp.																			09	-0.06
Total Avg. Input Power																			57	0.25
Data Rate																			70	0.28
Design Life																			25	0.33
TRL																			54	0.32
Year of Dev.																			07	0.22
Dev. Period																			09	0.36
Date of Launch																			00	0.28
Orbit																				1.00

OTA Cost has significant correlations with:
- Aperture Diameter
- Primary Mirror & System Focal Length (Volume)
- Pointing Stability (inverse correlation)
- OTA Mass
- Design Life

Total Cost has significant correlations with:
- Aperture Diameter
- Primary Mirror & System Focal Length (Volume)
- Pointing Stability (inverse correlation)
- OTA & Total Mass
- Average Power
- Design Life
- Development Period

No correlation for wavelength or temperature

TRL correlation is ‘weak’

Not all Correlated Variables are Independent

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Dev. Period																				0.36
Date of Launch																				0.28
Orbit																				1.00

Larger Diameter OTAs:

- have longer Focal Lengths
- have smaller Pointing Stability Requirements
- are just bigger and thus more Massive
- have larger instruments with are more Massive & require Power
- require bigger spacecraft which are more Massive & require Power
- need a long Design Life
- take longer to Develop
- are more Recent – older OTAs were smaller

All these variable are dependent on Aperture Diameter (co-linear).

Variable Linkages

rev. 8.1.11	Total Cost	OTA Cost	Aperture Diameter	PM F Len.	System F Len.	FOV	Pointing Stability	Total Mass	OTA Mass	Spectral Range minimum	Diff. Lim. λ	Operating Temp.	Total Avg. Input Power	Data Rate	Design Life	TRL	Year of Dev.	Dev. Period	Date of Launch	Orbit
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Total Cost	1.00	0.85	0.69	0.21	0.52	0.13	-0.72	0.68	0.85	0.21	-0.05	-0.11	0.57	0.05	0.30	-0.45	-0.15	0.70	0.03	0.46
OTA Cost		1.00	0.78	0.88	0.72	-0.13	-0.80	0.84	0.95	-0.16	-0.20	0.04	0.37	0.22	0.64	-0.61	-0.03	0.62	0.16	0.07
Aperture Diameter			1.00	0.36	0.72	-0.04	-0.71	0.59	0.84	0.51	0.46	-0.05	0.44	-0.10	0.43	-0.28	-0.08	0.45	0.05	0.05
PM F Len.				1.00	0.70	0.13	-0.77	0.69	0.89	-0.48	-0.38	0.18	0.21	0.04	0.56	-0.35	-0.11	0.41	0.11	0.00
System F Len.					1.00	-0.29	-0.47	0.61	0.70	0.02	-0.13	-0.04	0.13	-0.16	0.60	-0.38	-0.22	0.43	-0.03	0.18
FOV						1.00	-0.33	0.03	0.27	0.24	0.26	-0.12	0.10	0.19	-0.15	-0.31	0.19	-0.01	0.18	0.06
Pointing Stability							1.00	-0.62	-0.87	0.16	0.18	-0.13	-0.46	-0.03	-0.54	0.26	-0.04	-0.63	-0.24	-0.03
Total Mass								1.00	0.92	-0.10	0.10	0.01	0.39	-0.19	0.46	-0.54	-0.31	0.51	-0.16	0.24
OTA Mass									1.00	-0.22	-0.22	0.00	0.27	-0.17	0.41	-0.62	-0.04	0.69	0.18	-0.35
Spectral Range minimum																				0.12
Diff. Lim. λ																				0.26
Operating Temp.																				-0.06
Total Avg. Input Power																				0.25
Data Rate																				0.28
Design Life																				0.33
TRL																				0.32
Year of Dev.																				0.22
Dev. Period																				0.36
Date of Launch																				0.28
Orbit																				1.00

Correlation Matrix can be used to identify variable cross-linkages which should be reconciled with Engineering Judgment.

Aperture Diameter and Pointing Stability have a large negative correlation: Larger Diameter OTAs required smaller Pointing Stability.

Pointing Stability and OTA Mass have a large negative correlation: Small Pointing Stability requires a very stiff, i.e. Massive, OTA.

Wavelength and Temperature

rev. 8.1.11	Total Cost	OTA Cost	Aperture Diameter	PM F Len.	System F Len.	FOV	Pointing Stability	Total Mass	OTA Mass	Spectral Range minimum	Diff. Lim. λ	Operating Temp.	Total Avg. Input Power	Data Rate	Design Life	TRL	Year of Dev.	Dev. Period	Date of Launch	Orbit
units	(FY11$M)	(FY11$M)	(m)	(m)	(m)	(°)	(Arc-Sec / Sec)	(kg)	(kg)	(μ)	(μ)	(K)	(Watts)	(Kbps)	(months)	TRL	(year)	(months)	(year)	(km)
Total Cost	1.00	0.85	0.69	0.21	0.52	0.13	-0.72	0.68	0.85	0.21	-0.05	-0.11	0.57	0.05	0.30	-0.45	-0.15	0.70	0.03	0.46
OTA Cost		1.00	0.78	0.88	0.72	-0.13	-0.80	0.84	0.95	-0.16	-0.20	0.04	0.37	0.22	0.64	-0.61	-0.03	0.62	0.16	0.07
Aperture Diameter			1.00	0.36	0.72	-0.04	-0.71	0.59	0.84	0.51	0.46	-0.05	0.44	-0.10	0.43	-0.28	-0.08	0.45	0.05	0.05
PM F Len.				1.00	0.70	0.13	-0.77	0.69	0.89	-0.48	-0.38	0.18	0.21	0.04	0.56	-0.35	-0.11	0.41	0.11	0.00
System F Len.					1.00	-0.29	-0.47	0.61	0.70	0.02	-0.13	-0.04	0.13	-0.16	0.60	-0.38	-0.22	0.43	-0.03	0.18
FOV						1.00	-0.33	0.03	0.27	0.24	0.26	-0.12	0.10	0.19	-0.15	-0.31	0.19	-0.01	0.18	0.06
Pointing Stability							1.00	-0.62	-0.87	0.16	0.18	-0.13	-0.46	-0.03	-0.54	0.26	-0.04	-0.63	-0.24	-0.03
Total Mass								1.00	0.92	-0.10	0.10	0.01	0.39	-0.19	0.46	-0.54	-0.31	0.51	-0.16	0.24
OTA Mass									1.00	-0.22	-0.22	0.00	0.27	-0.17	0.41	-0.62	-0.04	0.69	0.18	-0.35
Spectral Range minimum										1.00	0.96	-0.24	0.16	0.10	0.06	-0.09	0.19	0.17	0.19	0.12
Diff. Lim. λ											1.00	-0.28	0.10	0.15	-0.20	0.12	0.35	0.23	0.32	0.26
Operating Temp.												1.00	0.12	-0.05	0.27	0.11	-0.06	-0.39	-0.09	-0.06
Total Avg. Input Power																			0.57	0.25
Data Rate																			0.70	0.28
Design Life																			0.25	0.33
TRL																			0.64	0.32
Year of Dev.																			0.97	0.22
Dev. Period																			0.09	0.36
Date of Launch																			1.00	0.28
Orbit																				1.00

As expected Spectral Range and

Diffraction Limit are highly correlated.

Operating Temperature are inversely correlated.

But neither are significantly correlated with Cost – probably because they cancel either other out.

Year and TRL

rev. 8.1.11	Total Cost	OTA Cost	Aperture Diameter	PM F Len.	System F Len.	FOV	Pointing Stability	Total Mass	OTA Mass	Spectral Range minimum	Diff. Lim. λ	Operating Temp.	Total Avg. Input Power	Data Rate	Design Life	TRL	Year of Dev.	Dev. Period	Date of Launch	Orbit
units	(FY11$M)	(FY11$M)	(m)	(m)	(m)	(")	(Arc-Sec / Sec)	(kg)	(kg)	(μ)	(μ)	(K)	(Watts)	(Kbps)	(months)	TRL	(year)	(months)	(year)	(km)
Total Cost	1.00	0.85	0.69	0.21	0.52	0.13	-0.72	0.68	0.85	0.21	-0.05	-0.11	0.57	0.05	0.30	-0.45	-0.15	0.70	0.03	0.46
OTA Cost		1.00	0.78	0.88	0.72	-0.13	-0.80	0.84	0.95	-0.16	-0.20	0.04	0.37	0.22	0.64	-0.61	-0.03	0.62	0.16	0.07
Aperture Diameter			1.00	0.36	0.72	-0.04	-0.71	0.59	0.84	0.51	0.46	-0.05	0.44	-0.10	0.43	-0.28	-0.08	0.45	0.05	0.05
PM F Len.				1.00	0.70	0.13	-0.77	0.69	0.89	-0.48	-0.38	0.18	0.21	0.04	0.56	-0.35	-0.11	0.41	0.11	0.00
System F Len.					1.00	-0.29	-0.47	0.61	0.70	0.02	-0.13	-0.04	0.13	-0.16	0.60	-0.38	-0.22	0.43	-0.03	0.18
FOV																.31	0.19	-0.01	0.18	0.06
Pointing Stability																.26	-0.04	-0.63	-0.24	-0.03
Total Mass																.54	-0.31	0.51	-0.16	0.24
OTA Mass																.62	-0.04	0.69	0.18	-0.35
Spectral Range minimum																.09	0.19	0.17	0.19	0.12
Diff. Lim. λ																.12	0.35	0.23	0.32	0.26
Operating Temp.																.11	-0.06	-0.39	-0.09	-0.06
Total Avg. Input Power													1.00	[illegible]	[illegible]	0.13	0.59	0.06	0.57	0.25
Data Rate														1.00	0.14	0.63	0.72	-0.09	0.70	0.28
Design Life															1.00	-0.15	0.12	0.15	0.25	0.33
TRL																1.00	0.67	-0.17	0.64	0.32
Year of Dev.																	1.00	-0.13	0.97	0.22
Dev. Period																		1.00	0.09	0.36
Date of Launch																			1.00	0.28
Orbit																				1.00

As expected, Year of Development and Launch year are highly correlated.

TRL is correlated with Year of Development because it did not exist for older missions and there is requirement not to start development until technology is at TRL-6.

Detailed Cross Correlation Matrix: Collector Variables

rev. 11.6.10	Total Cost	OTA Cost	Total Cost - OTA Cost	Areal Total Cost	Areal OTA Cost	Total Cost / kg	OTA Cost / kg	Aperture Diameter	PM F Len.	PM f#	System F Len.	System f#	OTA Volume	FOV	Pointing Stability	Total Mass	OTA Mass	Total Areal Density	OTA Areal Density	Spectral Range minimum	Diffraction Limited Wavelength	Operating Temperature	Avg. Input Power	Data Rate	Design Life	TRL	Year of Dev.	Dev. Period	Date of Launch	Orbit
units	(FY09$M)	(FY09$M)	(FY09$M)	(FY09$M /m2)	(FY09$M /m2)	(FY09$M /kg)	(FY09$M /kg)	(m)	(m)	unitless	(m)	unitless	(m3)	(°)	(Arc-Sec / Sec)	(kg)	(kg)	(kg/m2)	(kg/m2)	(μ)	(μ)	(K)	(Watts)	(Kbps)	(months)	TRL	(year)	(months)	(year)	(km)
Total Cost	1.00	0.88	1.00	-0.16	0.01	0.52	0.37	0.64	0.80	0.11	0.68	0.31	0.81	0.07	-0.62	0.93	0.76	-0.29	0.11	0.08	0.12	-0.05	0.65	0.19	0.69	-0.46	-0.07	0.58	0.17	0.36
OTA Cost		1.00	0.85	-0.45	0.18	0.12	0.23	0.82	0.82	0.03	0.72	0.33	0.85	-0.25	-0.82	0.90	0.91	-0.49	-0.05	-0.05	-0.07	-0.01	0.51	-0.06	0.65	-0.38	0.04	0.61	0.26	-0.02
Total Cost - OTA Cost			1.00	-0.14	-0.01	0.54	0.38	0.68	0.81	0.19	0.65	0.31	0.87	-0.01	-0.61	0.95	0.73	-0.28	0.08	0.09	0.16	0.02	0.71	0.29	0.68	-0.46	-0.02	0.59	0.19	0.33
Areal Total Cost				1.00	0.62	0.08	0.20	-0.86	-0.42	0.52	-0.53	0.18	-0.71	0.35	0.34	-0.21	-0.70	0.97	-0.17	-0.13	-0.28	0.14	0.14	0.24	-0.29	-0.39	-0.09	-0.15	-0.21	0.22
Areal OTA Cost					1.00	0.10	0.37	-0.42	-0.11	0.44	-0.28	-0.05	-0.28	0.26	-0.53	-0.04	0.05	0.64	0.47	-0.32	-0.58	-0.31	0.04	0.06	-0.14	-0.36	-0.33	0.09	-0.28	-0.14
Total Cost / kg						1.00	0.62	0.22	0.24	0.15	0.43	0.33	0.18	0.11	-0.15	0.18	0.14	-0.18	-0.20	0.23	0.01	-0.19	0.25	0.31	0.39	0.08	-0.01	0.33	0.09	0.55
OTA Cost / kg							1.00	0.10	-0.08	-0.46	0.29	0.35	0.03	-0.35	-0.03	0.08	-0.19	-0.11	-0.65	0.13	0.20	-0.33	0.37	0.50	0.17	0.89	0.33	0.15	0.28	0.65
Aperture Diameter								1.00	0.76	-0.29	0.80	0.11	0.97	-0.30	-0.79	0.64	0.87	-0.88	0.15	0.11	0.28	-0.08	0.14	-0.16	0.60	-0.29	0.01	0.40	0.19	-0.08
PM F Len.									1.00	0.40	0.78	0.39	0.89	0.19	-0.84	0.80	0.90	-0.45	0.27	-0.41	-0.21	0.18	0.15	0.09	0.59	-0.39	-0.07	0.57	0.12	-0.13
PM f#										1.00	-0.05	0.28	-0.06	0.49	-0.53	0.11	0.65	0.49	0.50	[illegible]	-0.68	0.22	-0.16	-0.05	0.09	-0.37	-0.23	0.26	-0.21	-0.20
System F Len.											1.00	0.69	0.86	-0.33	-0.40	0.65	0.71	-0.57	0.09	-0.07	-0.16	-0.04	-0.04	-0.26	0.65	-0.39	-0.23	0.35	-0.06	0.07
System f#												1.00	0.27	-0.18	-0.01	0.28	0.28	0.13	-0.01	-0.26	-0.57	0.04	-0.19	-0.19	0.36	-0.32	-0.38	0.06	-0.32	0.20
OTA Volume													1.00	-0.08	-0.90	0.83	0.89	-0.76	0.17	-0.27	0.05	0.09	0.28	0.14	0.60	-0.31	0.05	0.53	0.24	-0.07
FOV														1.00	-0.28	0.02	0.46	0.35	0.64	0.04	-0.11	-0.08	0.04	0.26	-0.16	-0.31	0.10	0.04	0.10	0.03
Pointing Stability															1.00	-0.57	-0.86	0.49	-0.60	0.38	0.36	-0.25	-0.32	-0.24	-0.57	0.17	0.07	-0.47	-0.07	0.05
Total Mass																1.00	0.83	-0.21	0.21	-0.02	0.13	-0.06	0.39	-0.03	0.58	-0.52	-0.20	0.57	0.01	0.17
OTA Mass																	1.00	-0.70	0.61	-0.32	-0.32	-0.03	0.20	-0.26	0.48	-0.62	-0.08	0.79	0.27	-0.49
Total Areal Density																		1.00	-0.01	-0.17	-0.28	0.13	0.01	0.14	-0.32	-0.49	-0.10	-0.15	-0.19	0.08
OTA Areal Density																			1.00	-0.13	-0.33	-0.12	-0.10	-0.54	[illegible]	-0.97	-0.39	0.44	-0.18	-0.81
Spectral Range minimum																				1.00	0.84	-0.56	0.13	0.08	-0.13	-0.09	0.27	0.10	0.29	0.14
Diffraction Limited Wavelength																					1.00	-0.41	0.13	0.08	-0.14	0.12	0.29	0.46	0.30	0.09
Operating Temperature																						1.00	[illegible]	[illegible]	[illegible]	0.11	0.08	[illegible]	0.03	0.00
Avg. Input Power																													52	0.23
Data Rate																													54	0.34
Design Life																													27	0.15
TRL																													64	0.33
Year of Dev.																													96	0.09
Dev. Period																												1.00	0.06	-0.18
Date of Launch																													1.00	0.06
Orbit																														1.00

Looking deeper confirms other Engineering Correlations:

Longer Wavelength OTAs have faster Primary Mirror F/#

Lower Areal Density OTAs have lower TRL (are less mature).

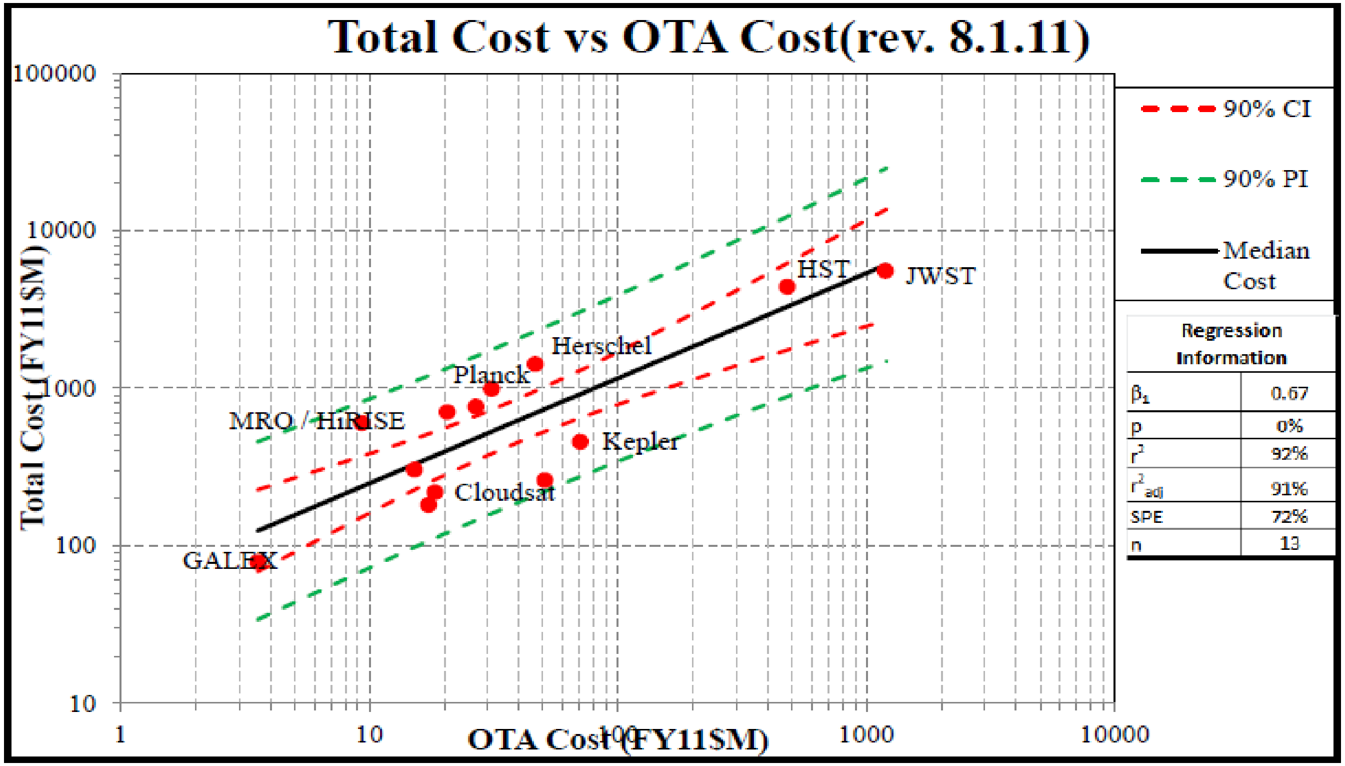
Agenda

- Introduction and Summary
- Data Collection Methodology
- Statistical Analysis Methodology
- What to Model?: OTA or Total Mission Cost
- Single Variable Modes: Mass and Diameter
- Multi-Variable Models
- Total Mission Cost Models
- Conclusions

OTA Cost or Total Cost

Engineering judgment says that OTA cost is most closely related to OTA engineering parameters.

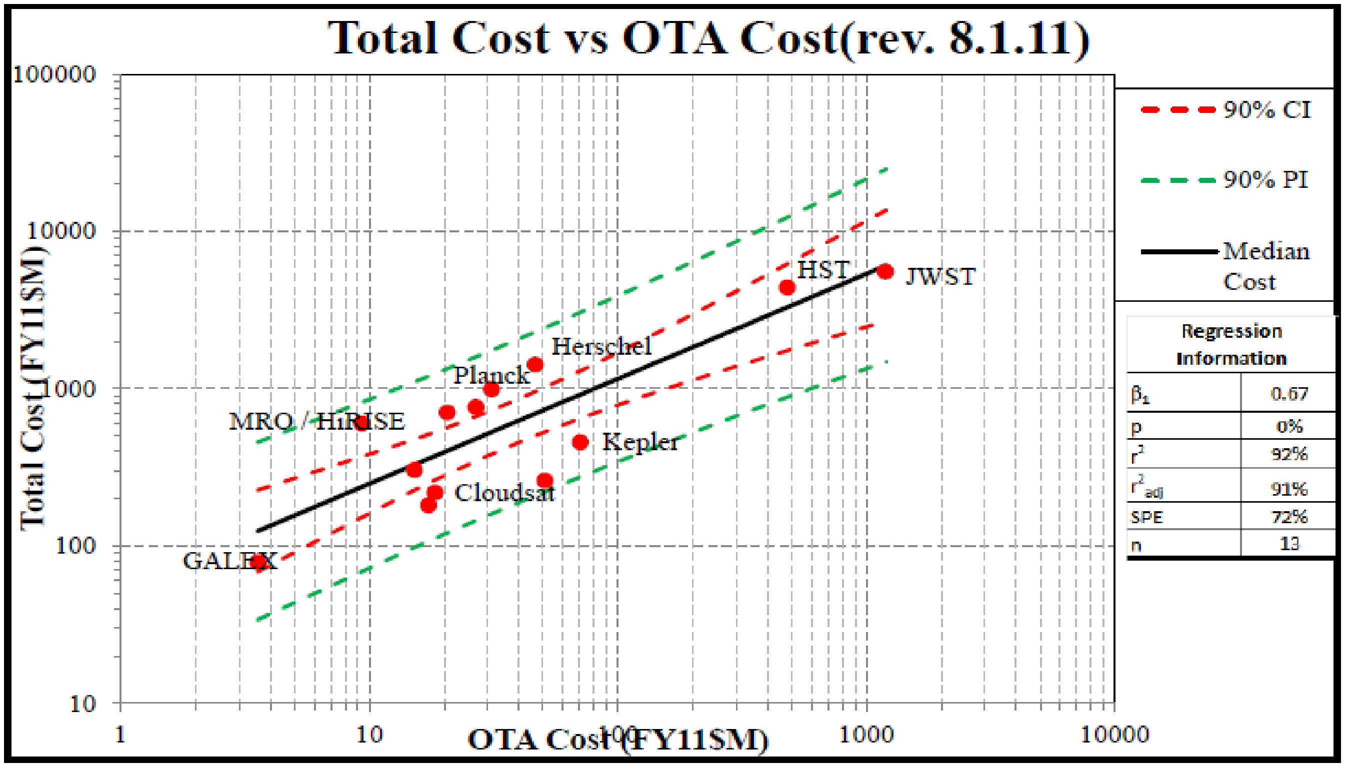
But, managers and mission planners are really more interested in total Phase A-D cost.



OTA Cost or Total Cost

Given that Total Cost tracks closely with OTA Cost, and that I'm an optics person and have accumulated mostly OTA data.

Our primary emphasis is to develop an OTA cost model.



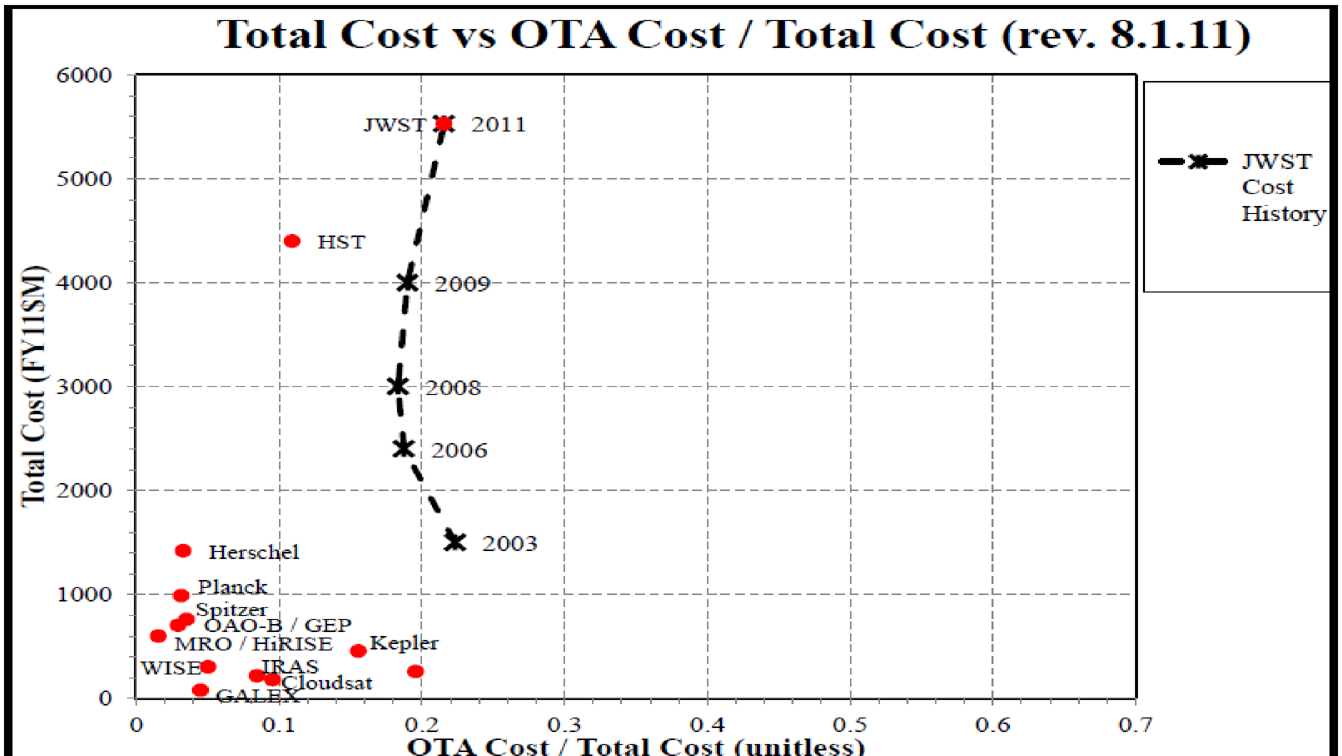
OTA vs Total Mission Cost

Given that OTA and Total Mission Costs appear to have a linear relationship, can the cost of one predict the cost of the other, i.e. is OTA cost a fixed percentage of Total Mission Cost?

Database % of Total

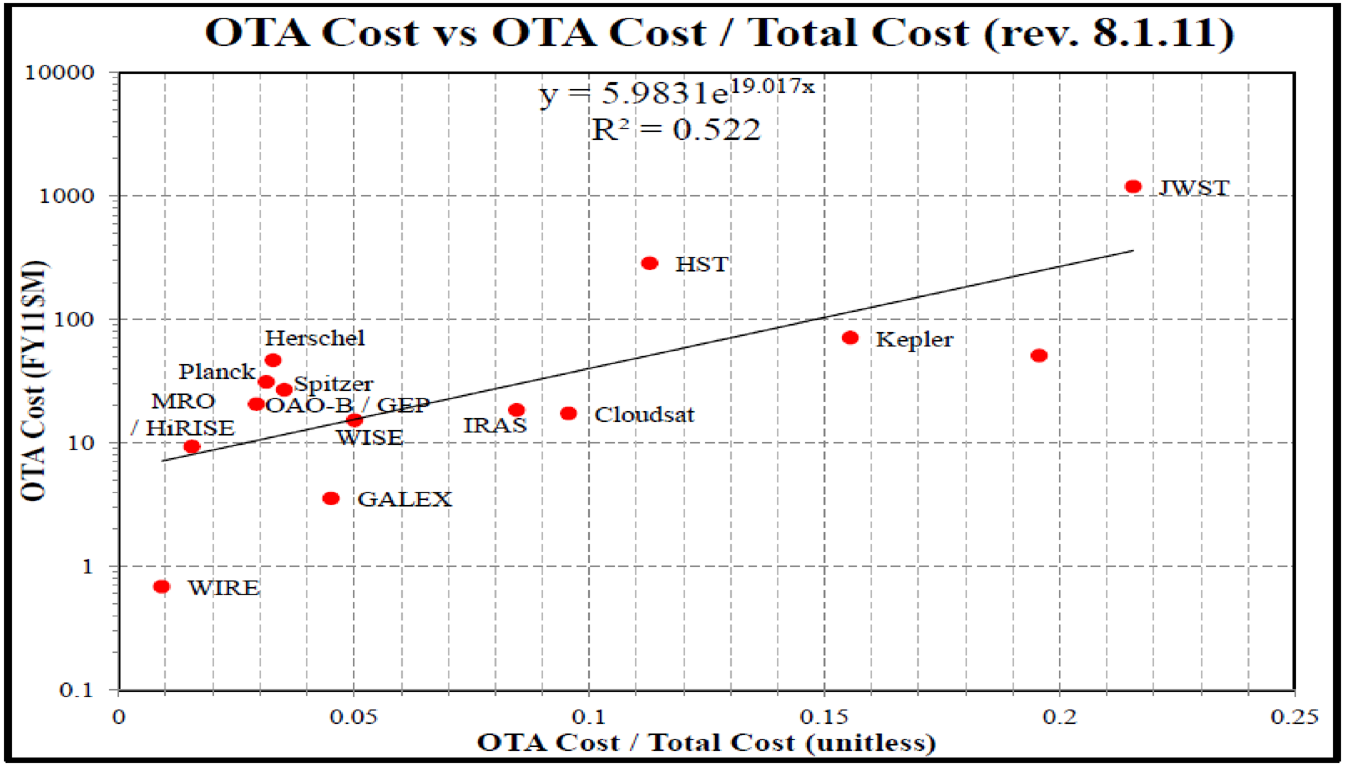
Data base clusters the percentage of OTA Cost as a function of the Total mission cost for the small missions.

JWST cost info is preliminary until JWST launches.



OTA Cost as a % of Total Mission Cost

- OTA Cost varies from approximately 1% to 25% of the Total.
- OTA's cost as % of Total depends upon need to develop custom tooling or infrastructure – or use existing.
- WIRE is clearly questionable & under review. Also, have asked GALEX to clarify their CADRe cost (missing Structure cost)



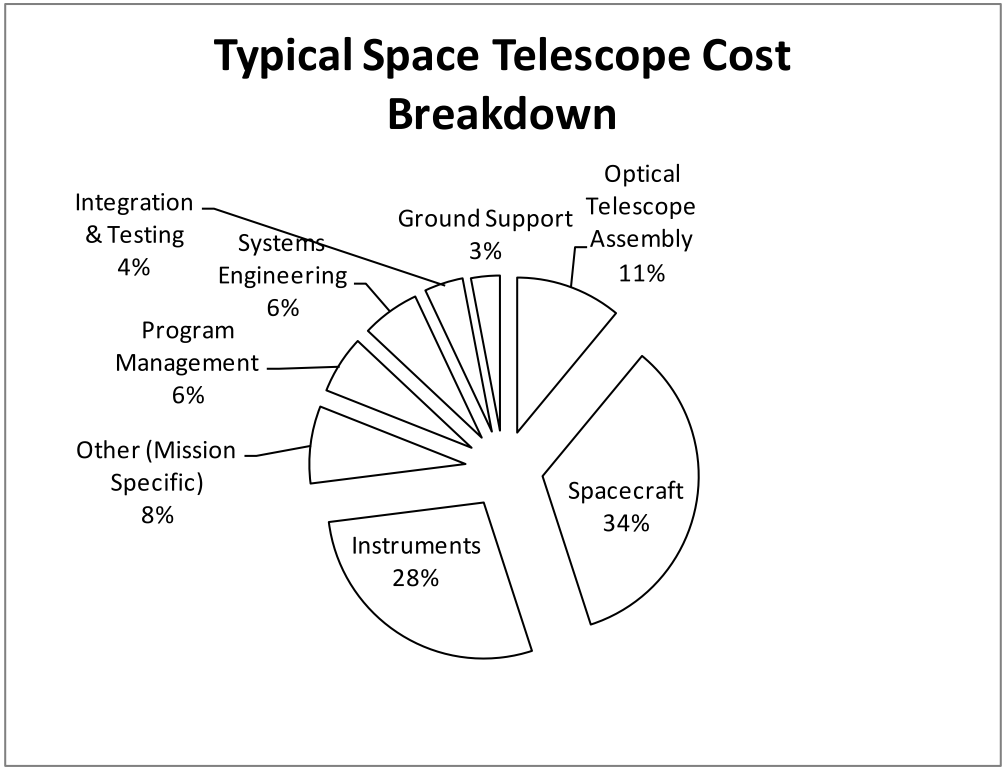
OTA Cost as a % of Total Mission Cost

We have detailed WBS data for 7 of the 14 free flying missions.

Mapping (5.3.11) database on common WBS gives OTA ~10% of Total

Some say that Power System is 20% of total mission Cost and Mass

For 1960/1970 mission, electronics costs are greater than OTA coss.



Agenda

- Introduction and Summary
- Motivation: 2000 NGST (JWST) Study
- Historical Models
- Data Collection Methodology
- Statistical Analysis Methodology
- What to Model?: OTA or Total Mission Cost
- **Single Variable Modes: Mass and Diameter**
- Multi-Variable Models
- Total Mission Cost Models
- Conclusions

OTA Cost Regression

Regressing on 15 normal incidence, 'free-flying' UVOIR OTAs

- Significant Variables: Diameter, Focal Length, Volume, Pointing & Mass
- FL has the highest R^2_{adj} and Mass has the lowest SPE
- Volume, FL & Diameter have acceptable R^2_{adj} & SPE (but they all Dia)

rev. 8.1.11		OTA Cost vs V1													
Variable Name		Aperture Diameter		PM F Len.		PM f/#		OTA Volume		FOV		Pointing Stability		OTA Mass	
Var.	p-value	1.42	0.00	1.55	0.00	0.58	0.57	0.58	0.00	-0.12	0.69	-0.76	0.02	1.08	0.00
Adjusted r^2		81%		94%		-3%		92%		4%		6%		86%	
SPE		123%		92%		707%		80%		400%		242%		58%	
n		15		11		11		11		12		8		13	

Variable Name		OTA Areal Density		Spectral Range minimum		Diff. Lim. λ		Operating Temp.		Year of Dev. (exp)		Date of Launch (exp)	
Var.	p-value	0.06	0.90	-0.07	0.56	-0.11	0.54	0.04	0.89	0.00	0.91	0.02	0.56
Adjusted r^2		-8%		-4%		-7%		-8%		-7%		3%	
SPE		810%		830%		787%		979%		1007%		747%	
n		12		15		12		14		14		15	

Mass Model

Mass Model

As an optical engineer, my preference is to develop a model based on an optical parameter, i.e. Aperture Diameter.

Aperture Diameter interests ‘users’ of space telescopes because it is directly proportional to sensitivity and resolution.

But, many believe that Mass is the most important CER.

Total system mass determines what vehicle can be used to launch.

Significant engineering costs are expended to keep a given payload inside of its allocated mass budget.

Such as light-weighting mirrors and structure.

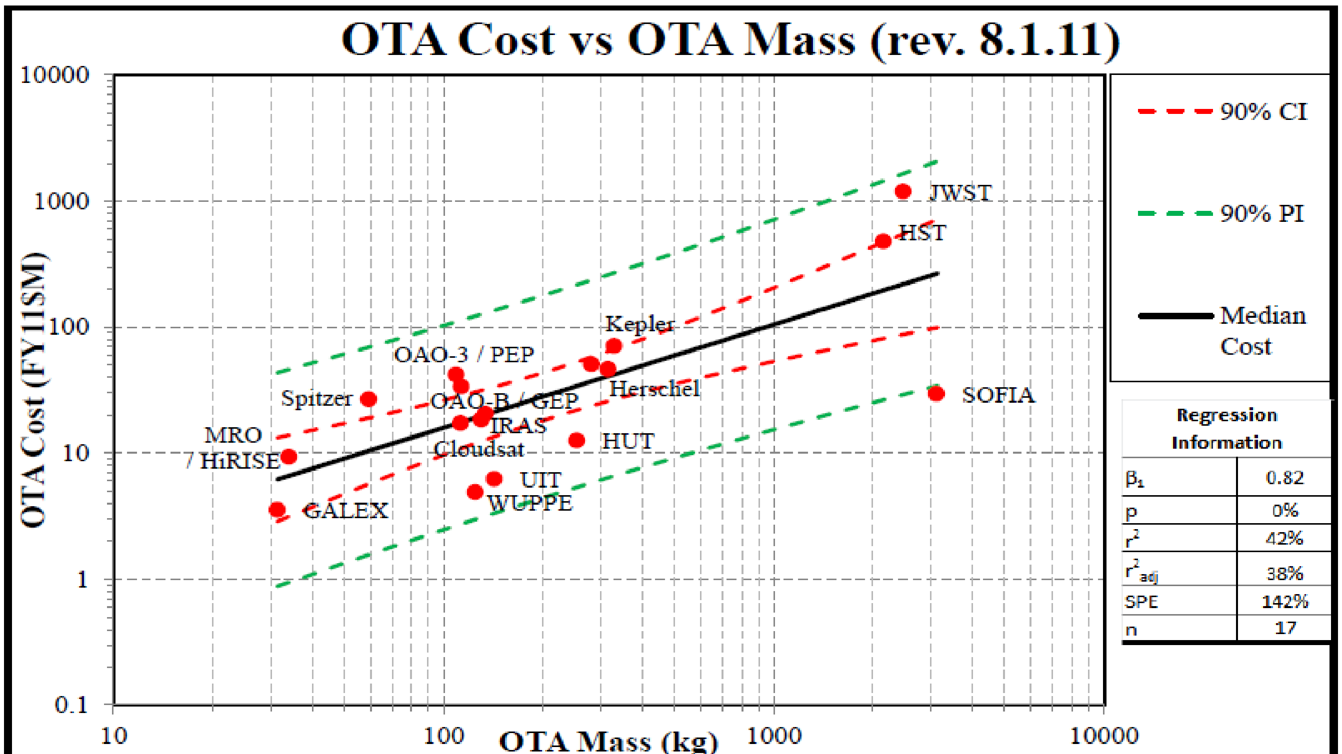
<u>Space telescopes are designed to mass</u>

OTA Cost Mass Model #1

Regressing on all OTAs in the data base:

OTA Cost ~ OTA Mass $^{0.8}$ ***(N = 17; r^2 = 42%; SPE = 142%)***

Mass accounts for only 42% of the cost variation & is noisy

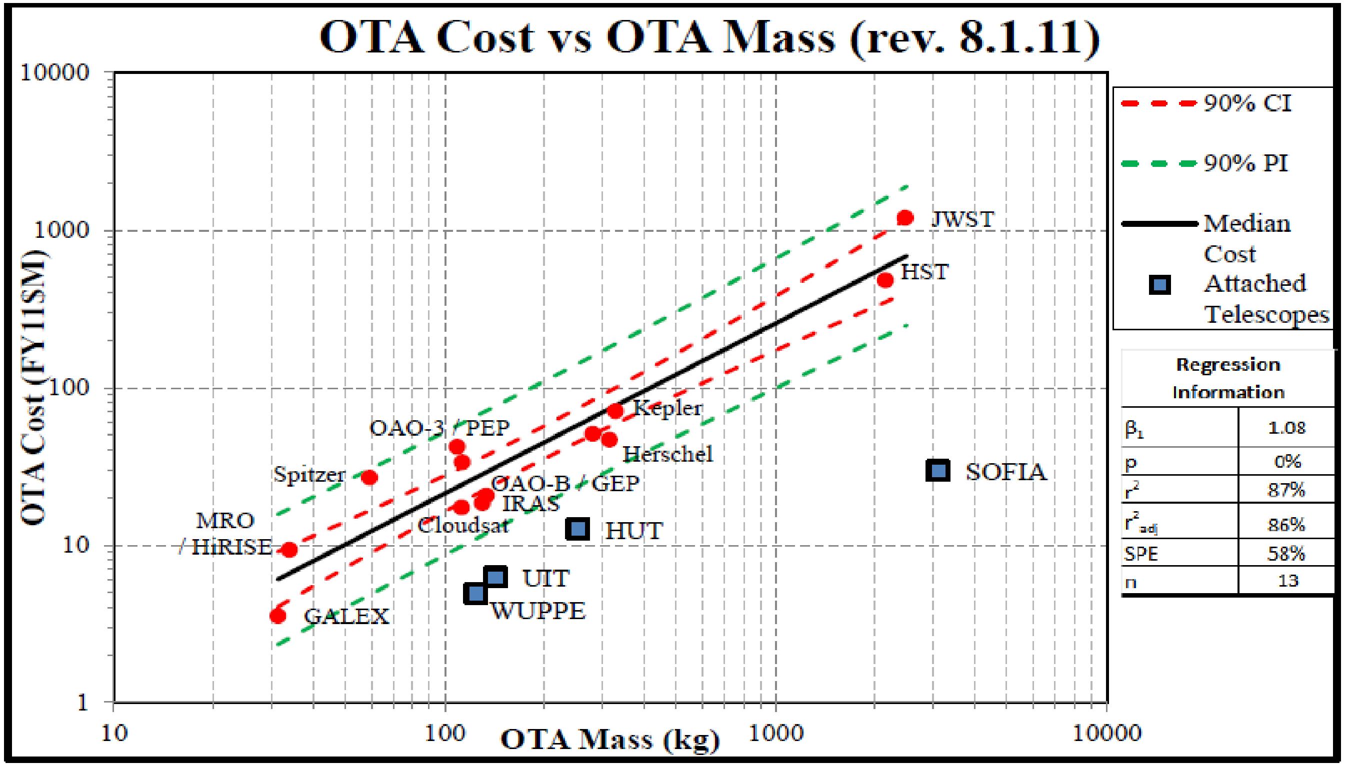


OTA Cost Mass Model #2

Regressing on only Free-Flyer (excluding 'attached' and SOFIA):

OTA Cost ~ OTA Mass $^{1.1}$ ***(N = 13; r^2 = 87%; SPE = 58%)***

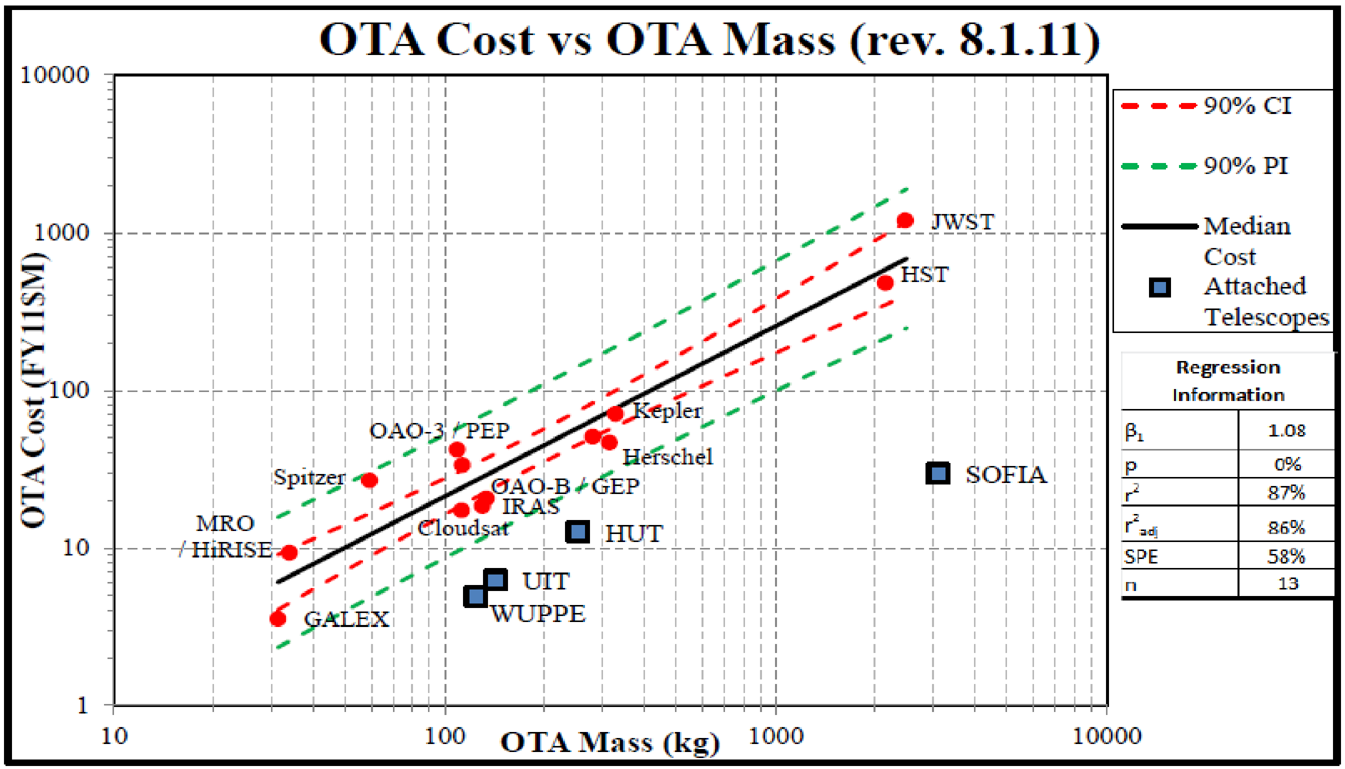
Mass accounts for 87% of the cost variation with less noise.



OTA Cost Mass Model #2

The 3 ‘attached’ missions & SOFIA clearly are a different ‘class’

They have a different set of design rules which allow them to have a lower cost for a given mass.

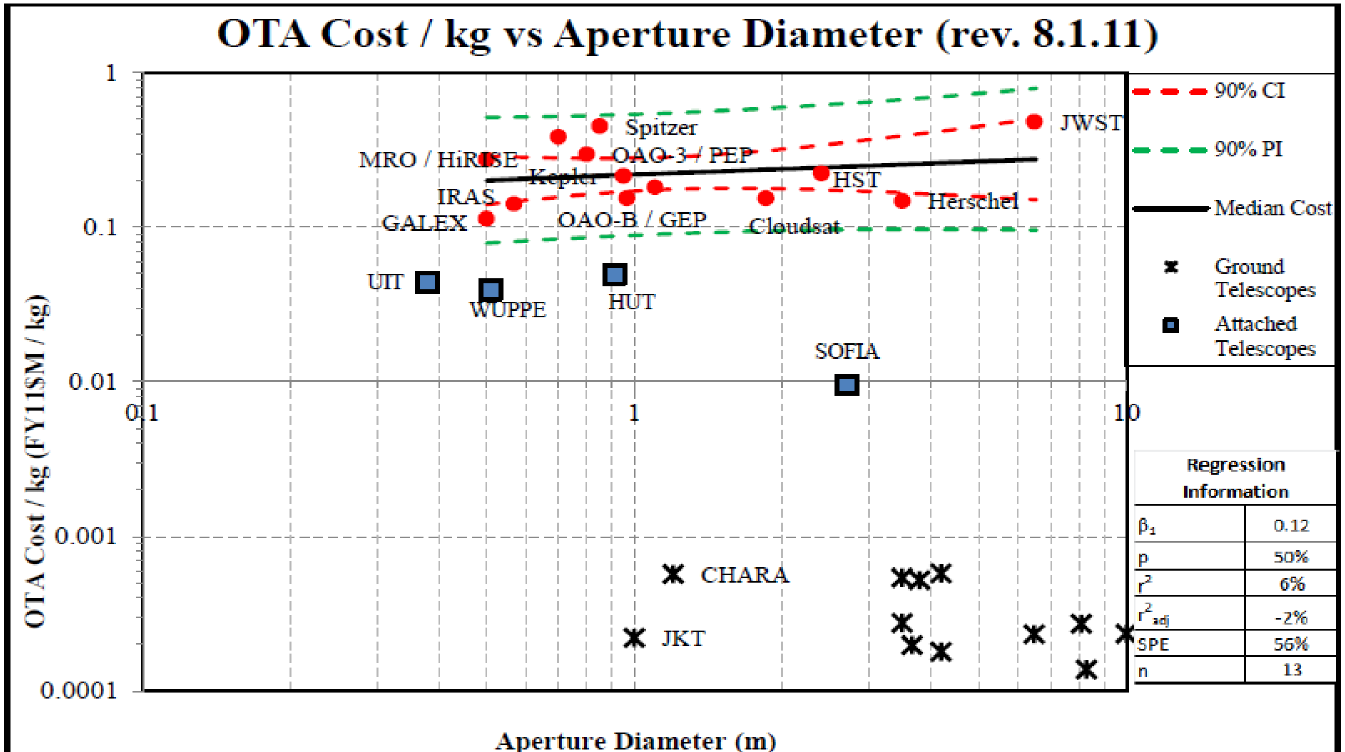


OTA Cost Density

It costs more to design & build a low mass OTA than a high mass OTA

Cost per kg depends on mission ‘type’; is independent of aperture size

- Free-Flying OTAs are ~2X more expensive per kg than Attached OTAs
- Free-Flying OTAs are ~15X more expensive per kg than SOFIA
- Free-Flying OTAs are 1000X more expensive per kg than Ground

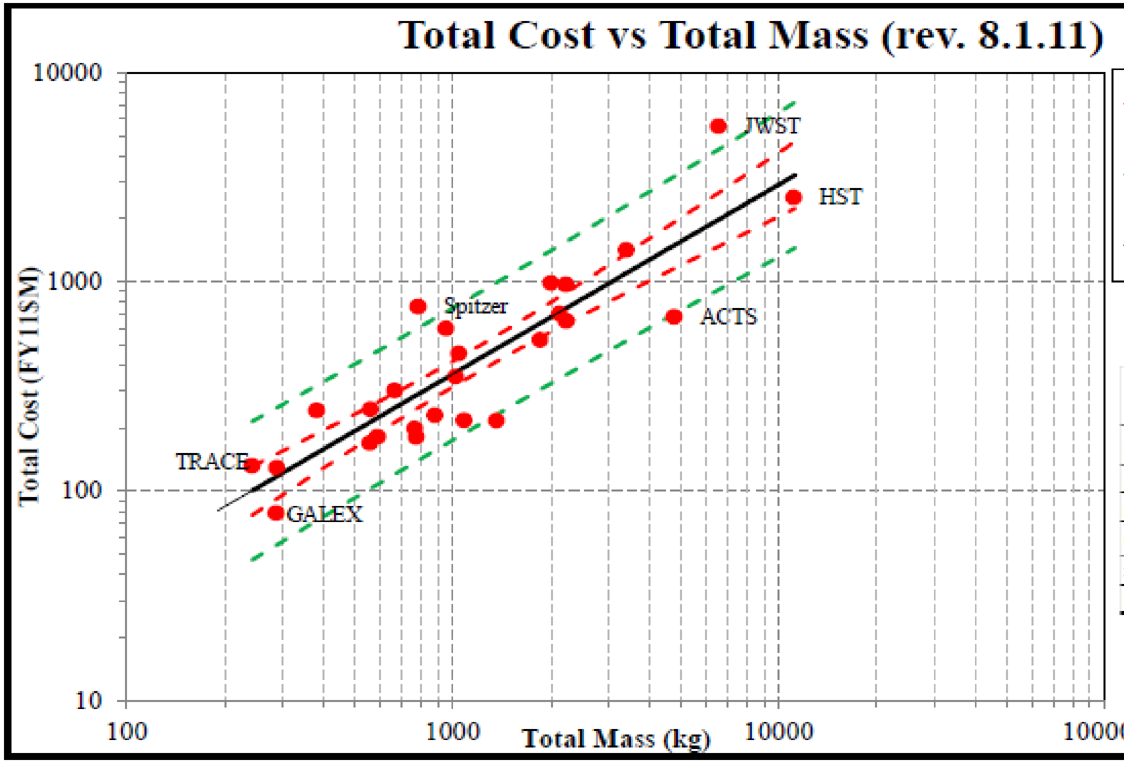


Mission Total Cost Mass Model

Regressing on only Free-Flyer (excluding 'attached' and SOFIA):

Total Cost ~ Total Mass $^{0.9}$ ***(N = 26; r^2 = 56%; SPE = 57%)***

Mass accounts for 56% of the Total Mission cost variation.



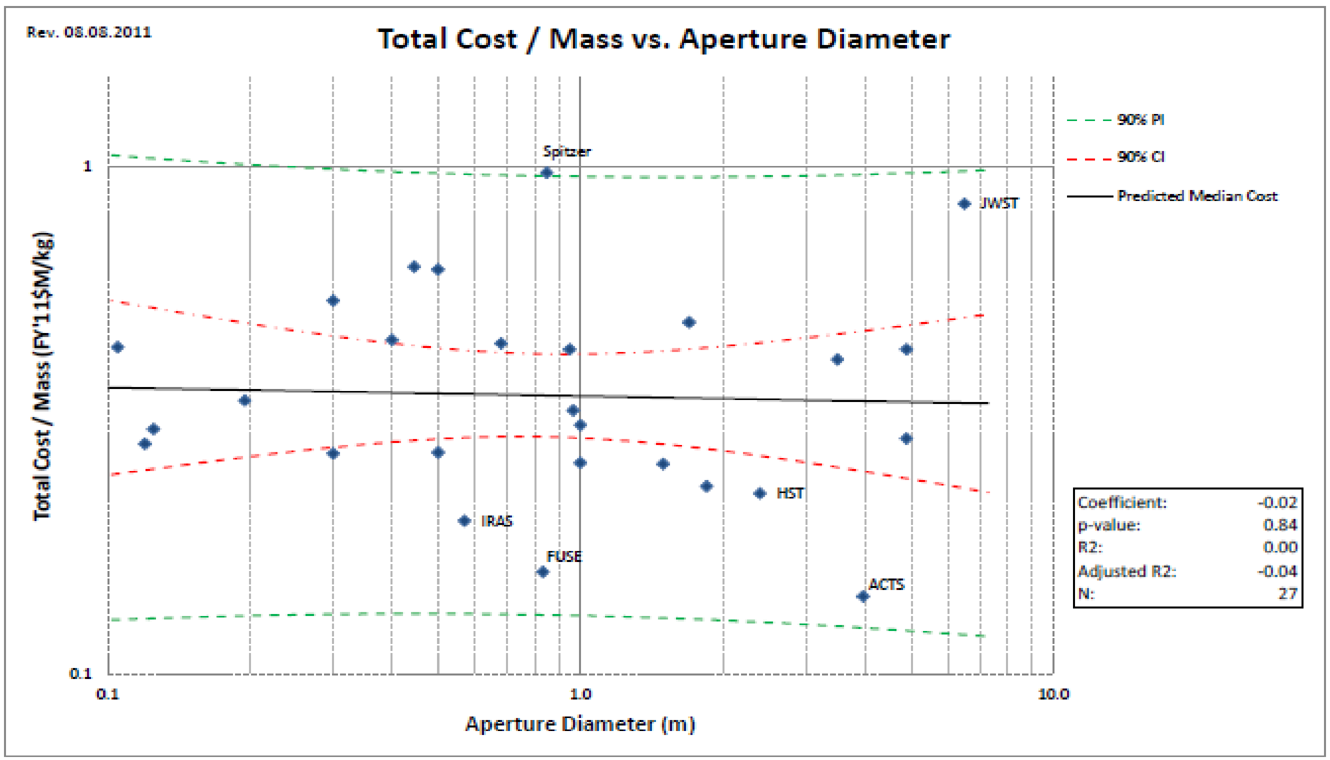
Regression Information	
β_1	0.91
p	0%
r^2	56%
r^2_{adj}	54%
SPE	57%
n	26

Total Mission Cost Density

Similar to OTA, all Space Mission have the same Cost/kg

Implies that all space missions have the same design rules.

Also, supports use of Mass Models



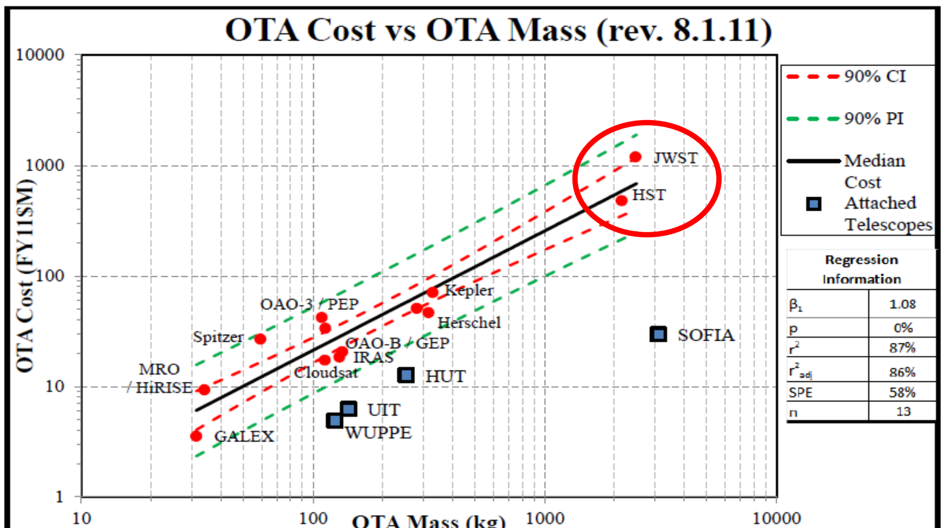
Mass is not a Good CER

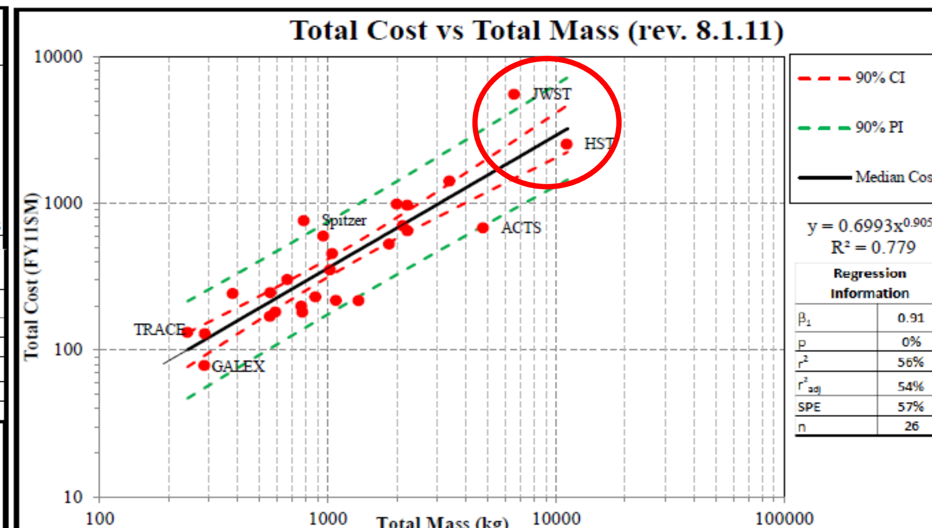
It may appear that Mass is a good CER, but it is not.

JWST & HST have same OTA mass, but JWST OTA costs is 2X HST

HST Total mass is 2X JWST, but JWST Total cost is 2X HST

The reason is complexity – JWST is more complex than HST





Problem with Mass

Mass may have a high correlation to Cost.

And, Mass may be convenient to quantify.

But, Mass is not an independent variable.

Mass depends upon the size of the telescope.

Bigger telescopes have more mass and Aperture drives size.

And, bigger telescopes typically require bigger spacecraft.

The correlation matrix says that Mass is highly correlated with:

Aperture Diameter, Focal Length and Pointing

<u>But in reality it is all Aperture, the others depend on aperture.</u>

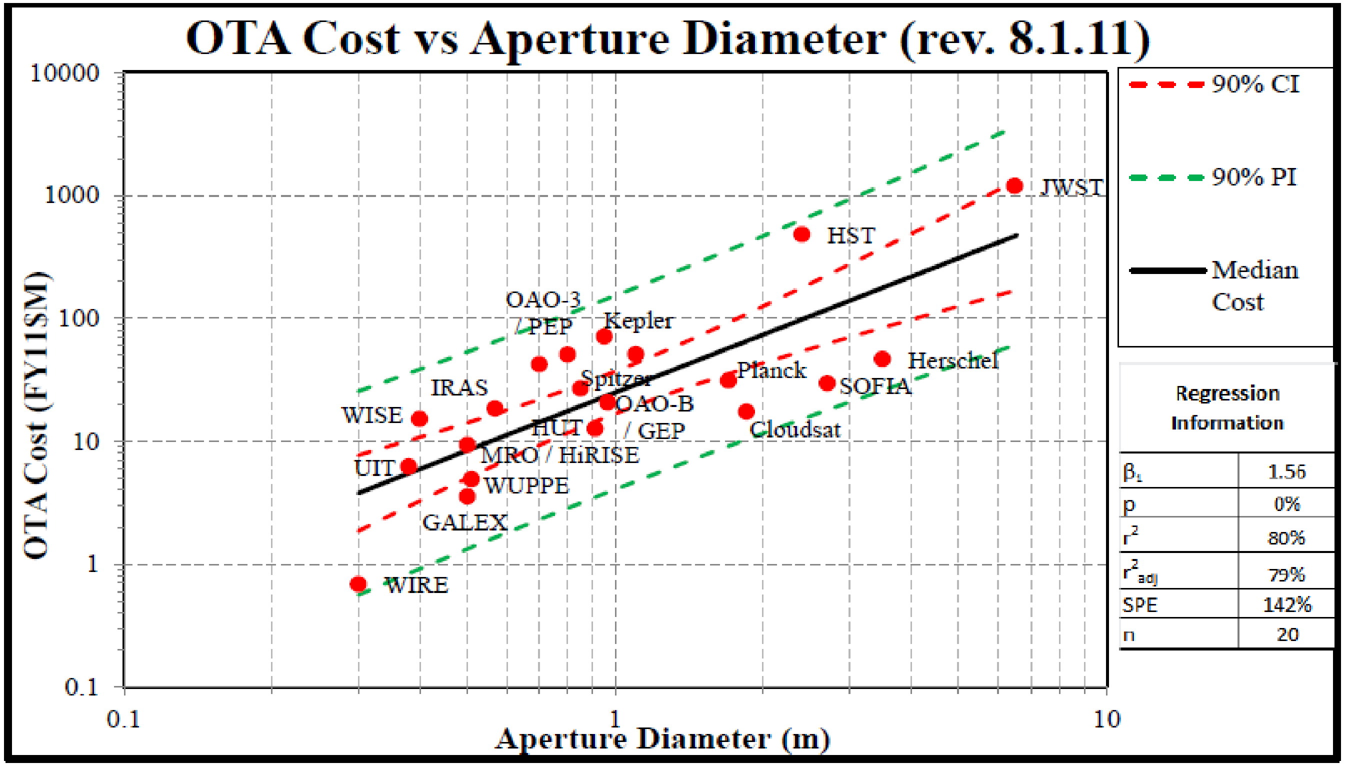
Aperture Model

OTA Cost vs Aperture Model #1

Regressing OTA Cost vs Aperture for all missions in database:

OTA Cost ~ Diameter $^{1.6}$ ***($N = 20$; $r^2 = 80\%$; $SPE = 142$)***

Diameter accounts for 80% of the cost variation, but is noisy

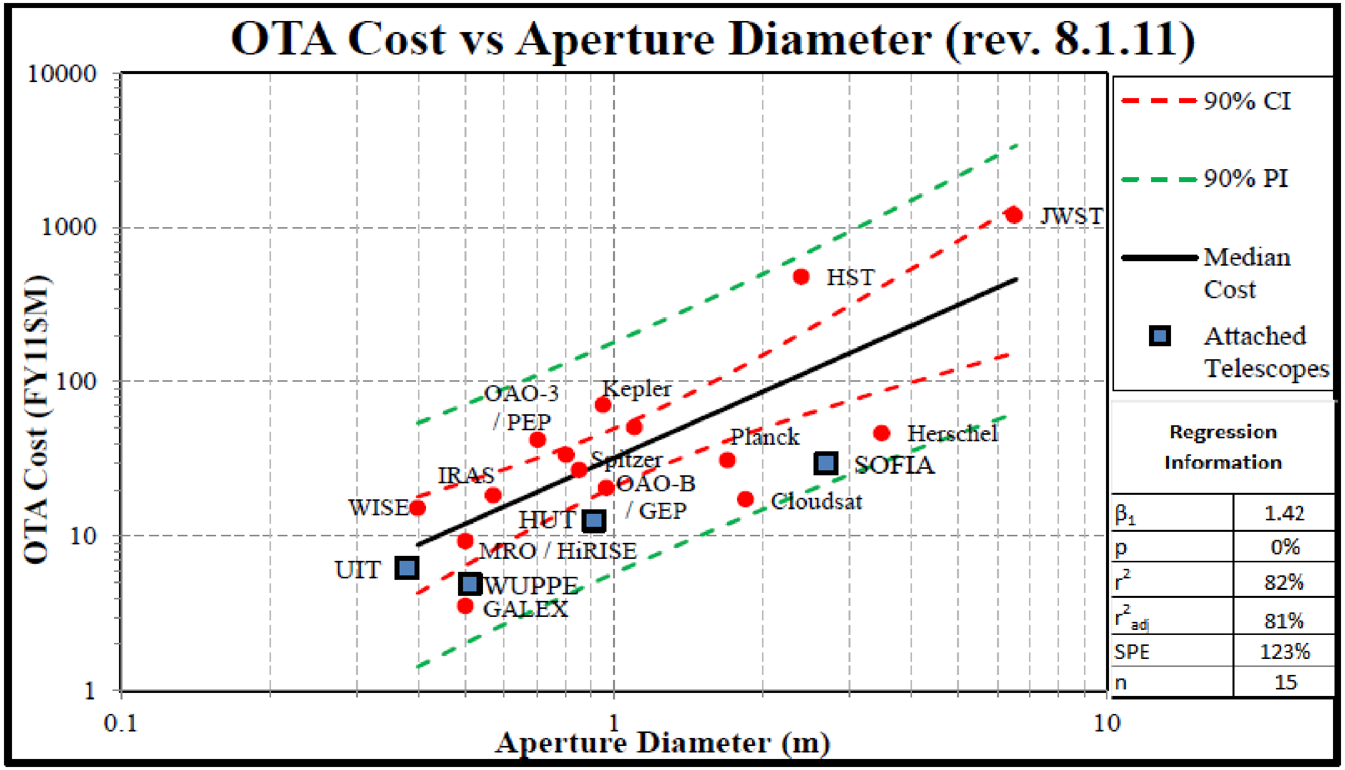


OTA Cost vs Aperture Model #2

Regressing OTA Cost vs Aperture for just Free-Flyer missions (and excluding WIRE):

OTA Cost ~ Diameter $^{1.4}$ ***(N = 15; r² = 82%; SPE = 123)***

Diameter accounts for 82% of the cost variation, is less noisy



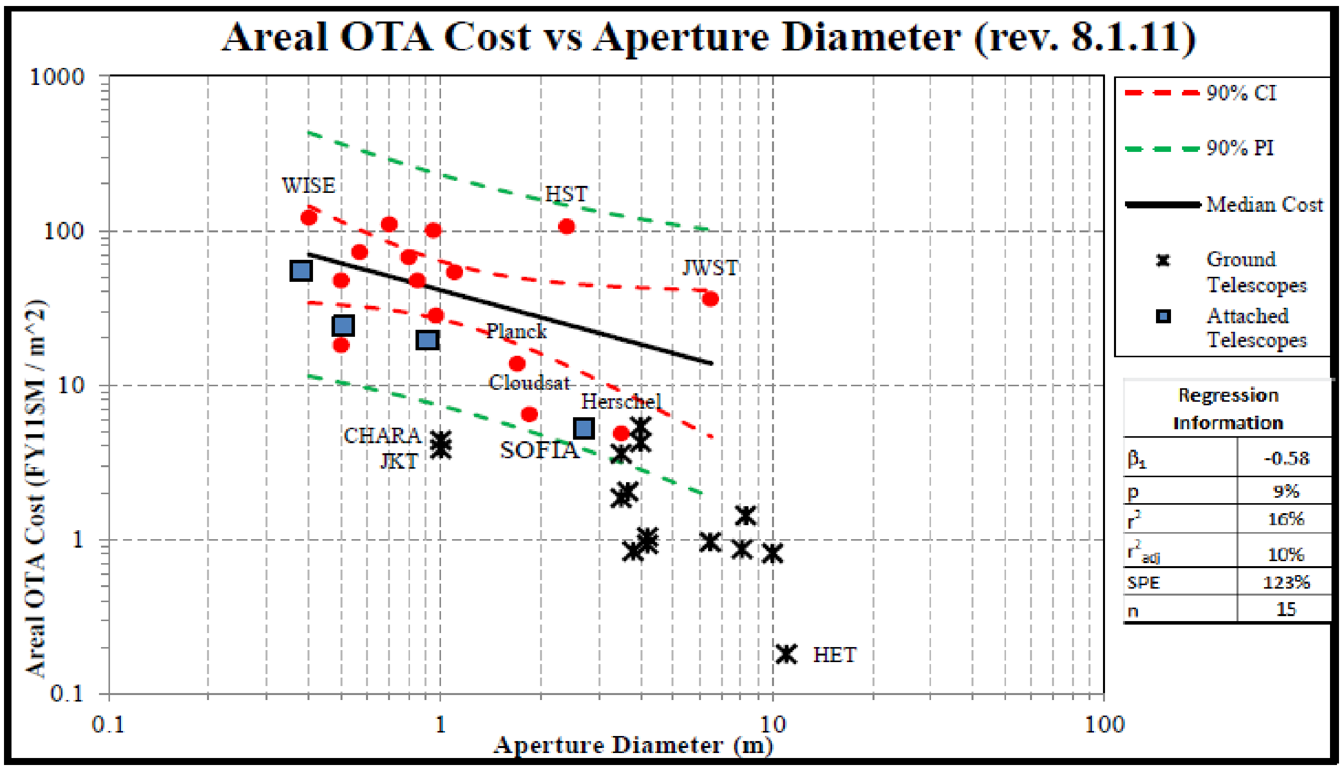
Regression Information	
β_1	1.42
p	0%
r^2	82%
r^2_{adj}	81%
SPE	123%
n	15

OTA Areal Cost

Because coefficient for diameter is less than ‘2’, the areal cost (cost per area) decreases as telescopes become larger.

Larger OTAs provide a higher ROI, less $ per photon.

Also, more massive ‘attached’ and ‘ground’ have lower areal cost



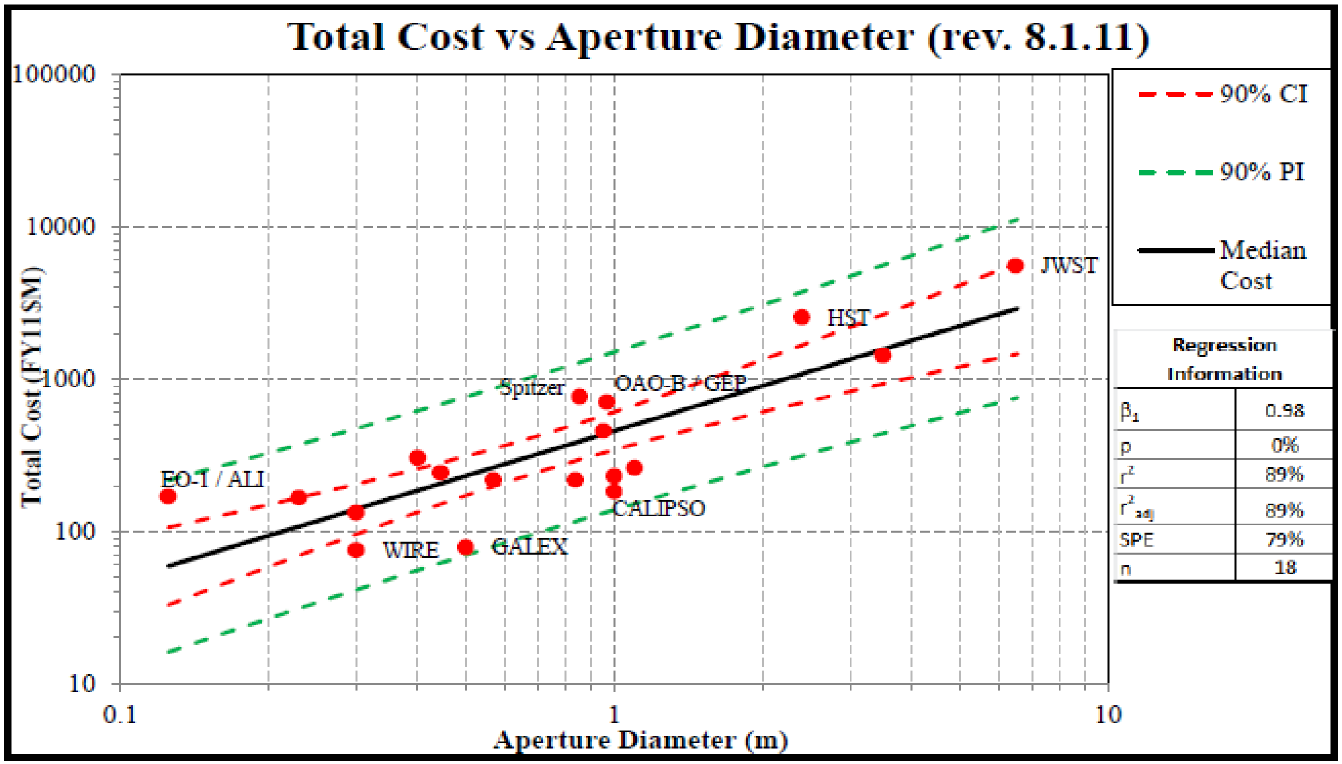
Total Mission Cost vs Aperture Model

Regressing Total Cost vs Aperture for free-flying UVOIR:

Total Cost ~ Diameter ^{1} ***(N = 18; r^2 = 89%; SPE = 79***

Diameter accounts for 89% of the cost variation

Because Total is ‘flatter’ than OTA, larger aperture are even more cost effective. Other costs (spacecraft, power, etc.) drive smaller aperture.



Agenda

- Introduction and Summary
- Data Collection Methodology
- Statistical Analysis Methodology
- What to Model?: OTA or Total Mission Cost
- Single Variable Modes: Mass and Diameter
- **Multi-Variable Models**
- Total Mission Cost Models
- Conclusions

Need for a second variable

Assuming that Mass is not the right CER and that Aperture is

Aperture Model only accounts for 70% of the cost variation.

Therefore, other variables must account for the remaining 30% of the cost variation.

Thus, a multi-variable model is required.

First step is a residual analysis.

How to develop a Multi-Variable Model

Perform multi-variable regression to add a second variable.

Select two variable model based on:

- Change in Significance of Diameter to Fit
- Significance of Variable #2 to Fit
- Increase in r^2_{adj}
- Decrease in SPE
- Multi-Collinearity

Some variables may increase r^2_{adj} and/or decrease SPE, but they are not significant or their coefficients are not consistent with engineering judgment or they are multi-collinear.

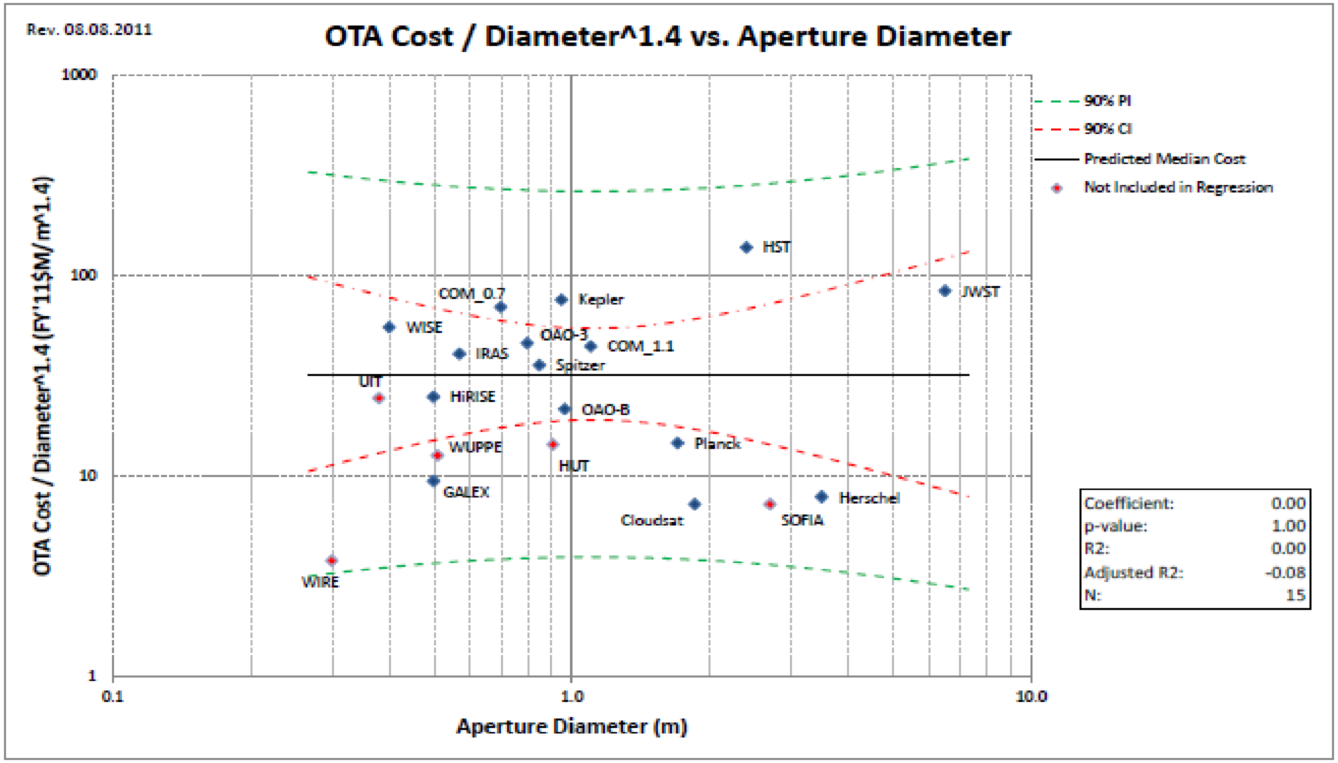
OTA Cost versus Diameter and V2

rev. 8.1.10		OTA Cost vs Aperture Diameter and V2													
Variable 2		Aperture Diameter		PM F Len.		OTA Volume		FOV		Pointing Stability		OTA Mass		OTA Areal Density	
Diam.	p-value	1.42	0.00	0.73	0.19	-1.28	0.38	1.26	0.02	1.64	0.01	0.02	0.94	2.05	0.00
Var. 2	p-value	-	-	1.00	0.06	1.00	0.06	0.00	1.00	-0.21	0.32	1.07	0.00	1.01	0.00
Adjusted r^2		81%		93%		93%		4%		95%		85%		84%	
SPE		123%		84%		84%		142%		66%		58%		54%	
n		15		11		11		12		8		13		12	
Multicollinearity?		N/A		Yes		Yes		No		No		Yes		No	
Variable 2		Spectral Range minimum		Diffraction Limited Wavelength		Operating Temperature		Design Life (exp)		Year of Dev. (exp)		Dev. Period (exp)		Date of Launch (exp)	
Diam.	p-value	1.62	0.00	1.54	0.00	1.49	0.00	0.83	0.02	1.45	0.00	1.14	0.04	1.46	0.00
Var. 2	p-value	-0.18	0.02	-0.22	0.02	-0.08	0.64	0.01	0.01	-0.01	0.46	0.01	0.17	-0.01	0.70
Adjusted r^2		96%		98%		81%		99%		84%		91%		82%	
SPE		74%		60%		136%		71%		124%		128%		120%	
n		15		12		14		15		14		13		15	
Multicollinearity?		No		No		No		No		No		No		No	

Diffraction Limit & Spectral Min are most significant, both increase R2 & decrease SPE
OTA Mass increases R2 to 85%, but is multi-colinear with Aperture Diameter.
Other mult-colinear variables are FL and Volume
Don’t understand impact of Design Life on Diameter.

Aperture Residual Error Analysis

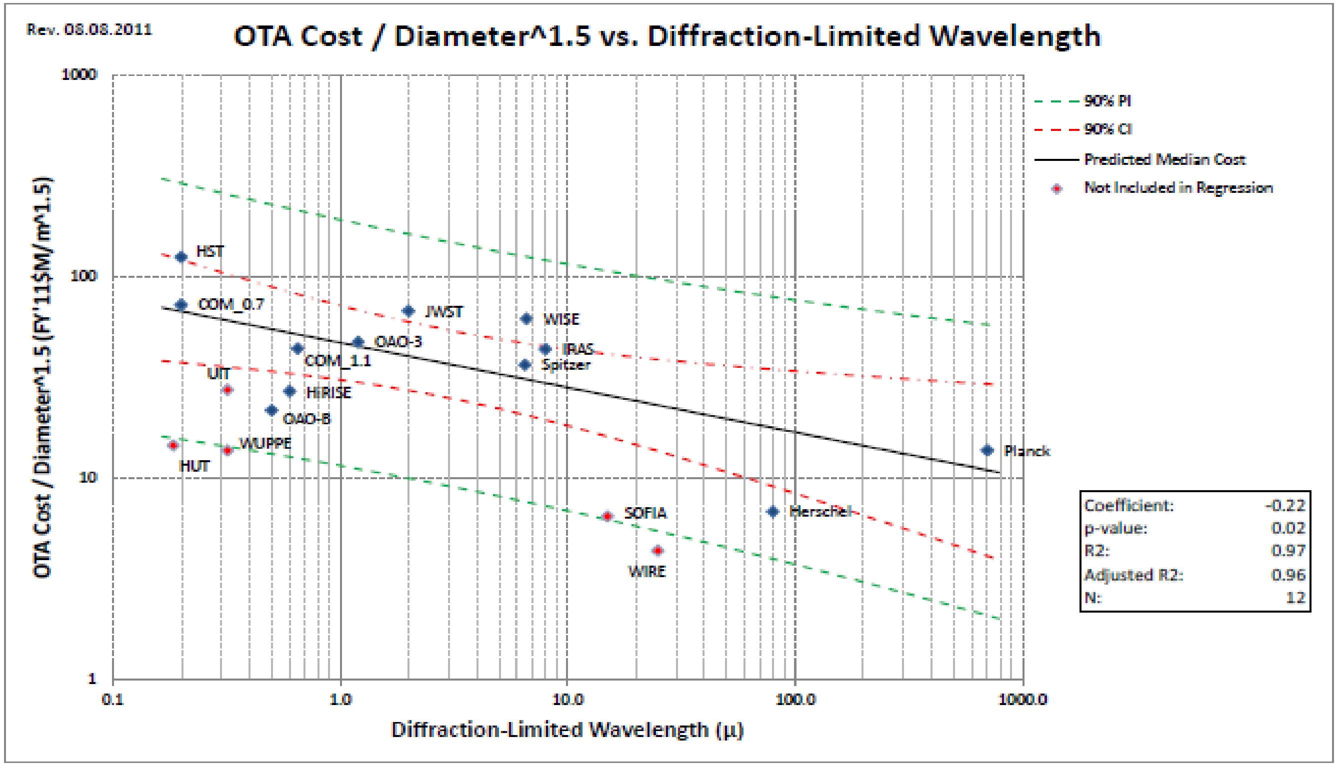
- Divide data by Diameter Model (normalize data) and plot as a function of Variables.
- R^2 indicates how % of residual error explained by a 2nd Variable
- For example, as expected diameter explains 'zero' variation



Aperture Residual Error Analysis: Wavelength

Diffraction Limit Wavelength explains 97% of residual variation

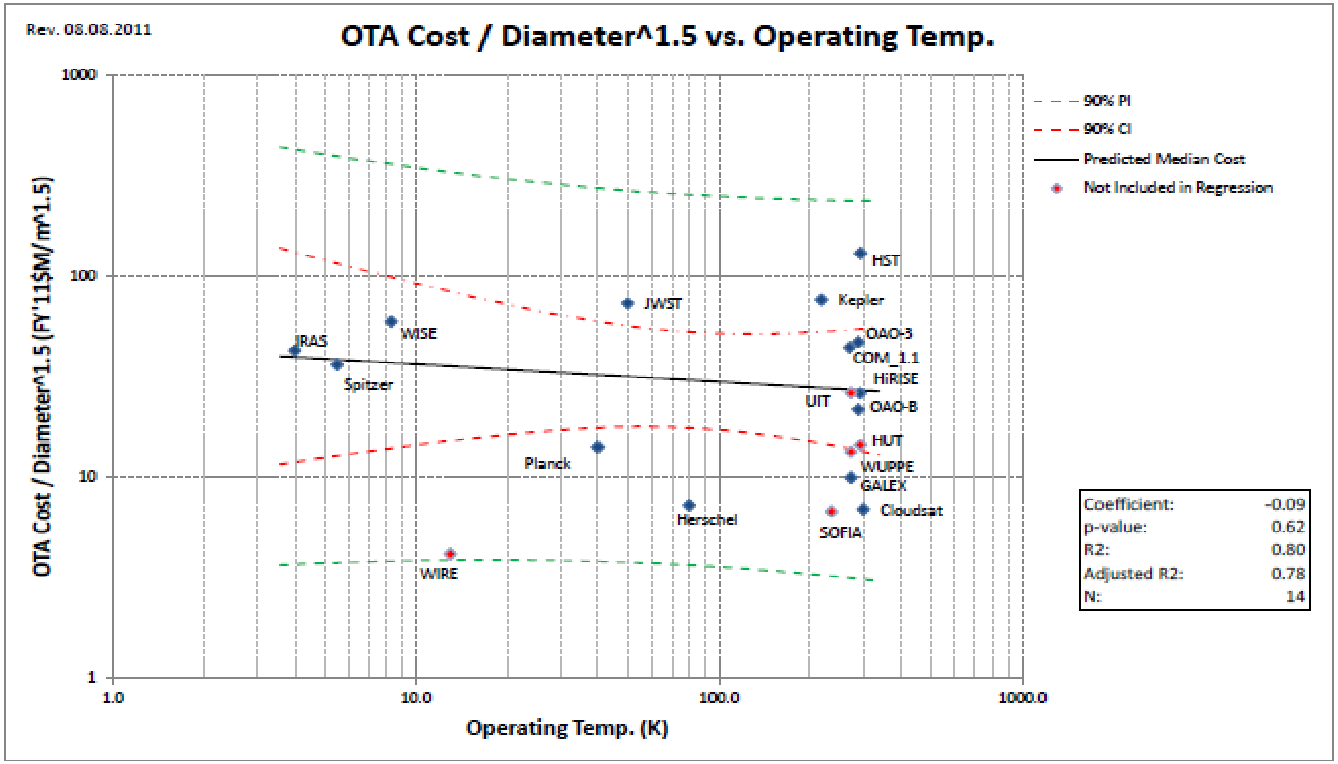
A -0.2 coefficient implies that an OTA with a 10X longer wavelength will cost 40% less.



Aperture Residual Error Analysis: Temperature

Operating Temperature does not significantly explain residual aperture variation

But, it might be a good 3rd or 4th CER parameter

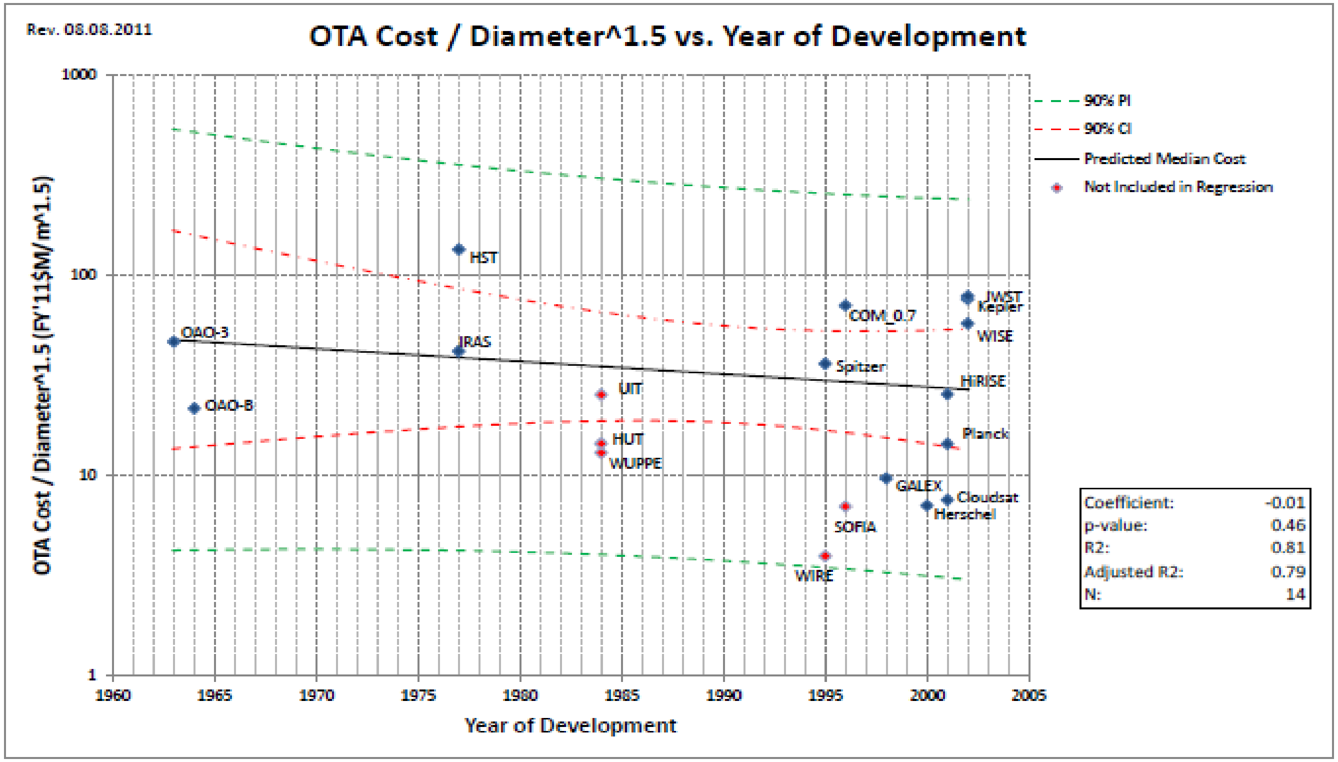


Aperture Residual Error Analysis: YOD

Year of Development does not significantly explain residual.

But, it might be a good 3rd or 4th CER parameter

Concern that YOD is correlated with Aperture and Wavelength. Also, what is role of spectroscopic vs imaging.

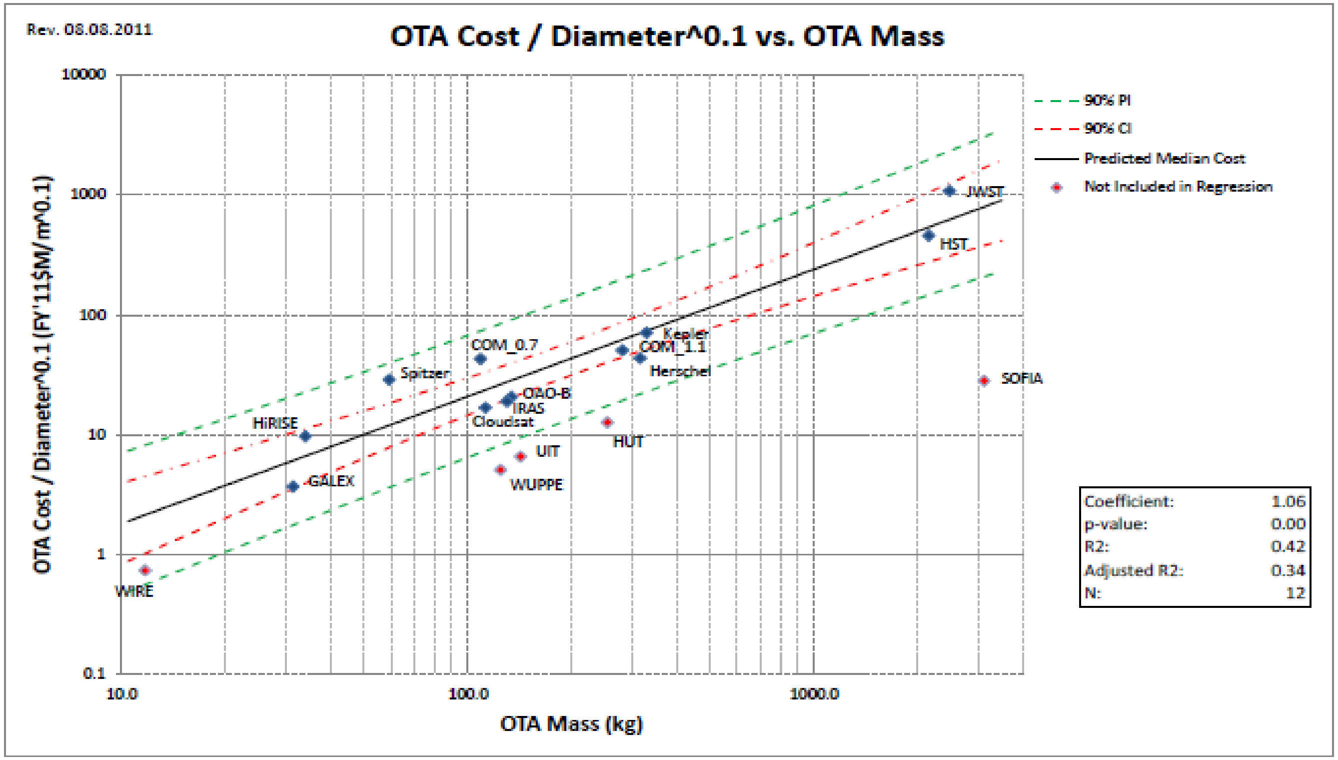


Aperture Residual Error Analysis: Mass

Mass explains some residual aperture variation

(p = 0.0; R2 = 0.42)

BUT it is multi-colinear with Aperture Diameter



Two Variable Aperture Model

Two second variables best meet all the criteria:

Wavelength Diffraction Limit and

Spectral Minimum

Diffraction Limited Wavelength yields the best model:

OTA Cost ~ Dia$^{1.6}$ $\lambda^{-0.25}$ ***(N = 12, r^2 = 98%; SPE= 60%)***

OTA Cost versus Diameter, Wavelength and V3

Operating Temperature is the only significant 3rd variable

OTA Cost ~ D $^{1.7}$ $\lambda^{-0.3}$ T$^{-0.25}$

(N = 11, r^2 = 96%; SPE= 54%)

More effort is required to understand issues related to:

- Design Life
- Year of Development

rev. 8.1.10		OTA Cost vs Diam., Diff. Lim., and V2									
	Variable 2	Diam., Diff. Lim., & V3		FOV		Pointing Stability		OTA Mass		OTA Areal Density	
Diam.	p-value	1.54	0.00	1.37	0.01	1.48	0.10	0.66	0.24	1.97	0.00
Diff. Lim	p-value	-0.22	0.02	-0.23	0.09	-0.11	0.66	-0.16	0.22	-0.16	0.22
V3	p-value	-	-	0.13	0.66	-0.18	0.56	0.66	0.07	0.66	0.07
Adjusted r^2		98%		84%		98%		92%		92%	
SPE		60%		73%		49%		46%		46%	
n		12		10		6		10		10	
Multicollinearity?		N/A		No		Yes		Yes		No	
	Variable 2	Operating Temperature		Design Life (exp)		Year of Dev. (exp)		Dev. Period (exp)		Date of Launch (exp)	
Diam.	p-value	1.70	0.00	0.87	0.03	1.53	0.00	1.45	0.01	1.49	0.00
Diff. Lim	p-value	-0.32	0.01	-0.05	0.66	-0.24	0.04	-0.18	0.06	-0.24	0.02
V3	p-value	-0.25	0.10	0.01	0.05	0.01	0.75	0.01	0.42	0.01	0.58
Adjusted r^2		96%		99%		97%		96%		97%	
SPE		54%		43%		60%		48%		58%	
n		11		12		11		10		12	
Multicollinearity?		No		Yes		No		No		No	

Three Variable Aperture Model

Three variable which best meet all the criteria:

- Wavelength Diffraction Limit
- Spectral Minimum and
- Operating Temperature

$$\textbf{OTA Cost} \sim \mathbf{D^{1.7}\ \lambda^{-0.3}\ T^{-0.25}}$$

(N = 11, r^2 = 96%; SPE= 54%)

More effort is required to understand issues related to:

- Design Life
- Year of Development

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Mission Cost

Assume that we have a viable cost model for OTAs, the next step is models for estimating Mission Cost.

Question is whether it is better to develop a model for Total Cost, or (Total – OTA) Cost.

Regressing the two costs as a function of variables

- No statistical difference in the coefficients
- (Total-OTA) is less noisy.

Will use (Total – OTA) which assume a cost model of the form:

Mission Cost ~ OTA Cost + Other Costs

Need to remember that OTA Cost is only approx 10% of Mission Cost

Total Mission Cost Regression

For 29 normal incidence, 'free-flying', significant variables are:

- System Focal Length and Diameter – relates to Volume
- Total Mass and Total Power
- Design Life – relates to reliability; but the coefficient is small
- Design Period is obvious – the longer the program, the more it costs

rev. 8.8.11		Total Cost vs V1																	
Variable Name		Aperture Diameter		System F Len.		FOV		Pointing Stability		Total Mass		Total Areal Density		Spectral Range minimum		Diff. Lim. λ		Operating Temp.	
Var.	p-value	0.53	0.00	0.55	0.00	0.04	0.72	-0.46	0.02	0.93	0.00	-0.15	0.14	0.02	0.63	-0.01	0.92	-0.03	0.82
Adjusted r^2		0.40		0.89		-0.05		0.25		0.55		0.05		-0.04		-0.05		-0.03	
SPE		126%		90%		195%		162%		60%		237%		317%		341%		310%	
n		29		20		22		11		27		27		28		19		27	

Variable Name		Total Avg. Input Power		Data Rate		Design Life (exp)		TRL		Year of Dev. (exp)		Dev. Period (exp)		Date of Launch (exp)		Orbit	
Var.	p-value	0.40	0.02	-0.01	0.91	0.01	0.00	-1.03	0.30	-0.01	0.54	0.03	0.00	0.01	0.79	0.13	0.01
Adjusted r^2		0.25		-0.03		0.73		0.18		-0.04		0.90		0.01		0.01	
SPE		203%		300%		115%		242%		344%		102%		298%		283%	
n		27		24		27		8		26		24		27		23	

(Total Mission – OTA) Cost Regression

Regressing on 23 ‘free-flying’ with Total & OTA cost data:

- System Focal Length and Diameter – relates to Volume
- Total Mass and Total Power
- Design Life – relates to reliability; but the coefficient is small
- Design Period is obvious – the longer the program, the more it costs

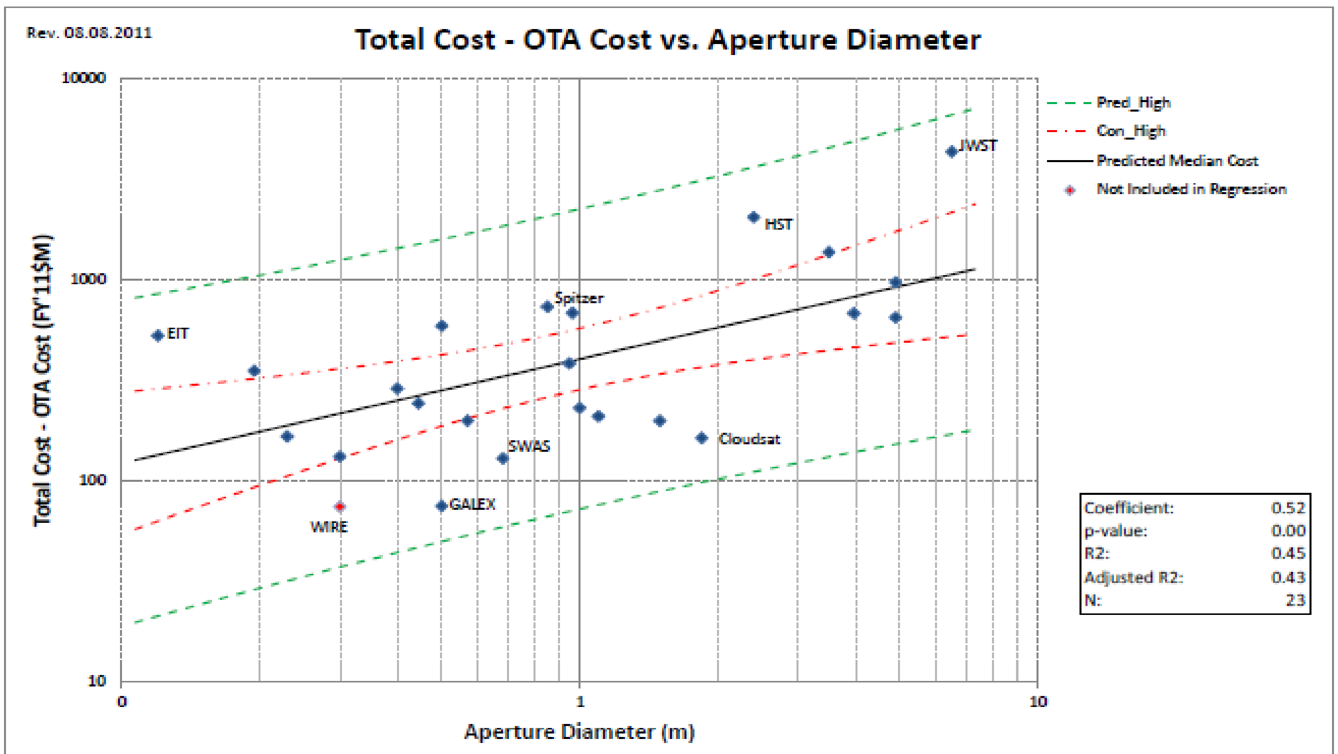
rev. 8.8.11	Total Cost - OTA Cost vs V1								
Variable Name	Aperture Diameter	System F Len.	FOV	Pointing Stability	Total Mass	Total Areal Density	Spectral Range minimum	Diff. Lim. λ	Operating Temp.
Var.	0.52	0.48	-0.21	-0.38	0.86	-0.11	0.00	-0.02	-0.06
p-value	0.00	0.01	0.31	0.05	0.00	0.36	0.92	0.83	0.74
Adjusted r^2	0.42	0.86	0.12	0.22	0.55	0.03	-0.04	-0.06	-0.04
SPE	119%	85%	126%	152%	58%	206%	247%	267%	249%
n	23	16	16	10	21	21	22	15	21

Variable Name	Total Avg. Input Power	Data Rate	Design Life (exp)	TRL	Year of Dev. (exp)	Dev. Period (exp)	Date of Launch (exp)	Orbit
Var.	0.34	0.01	0.01	-0.90	-0.01	0.02	0.00	0.10
p-value	0.04	0.83	0.00	0.43	0.64	0.00	0.87	0.06
Adjusted r^2	0.23	-0.03	0.71	0.04	-0.05	0.89	0.00	-0.01
SPE	172%	216%	103%	222%	274%	104%	247%	245%
n	21	18	21	6	20	18	21	18

(Total – OTA) Cost vs Diameter

Mission Cost increases with aperture because larger telescope require larger spacecraft, power, communications, etc:

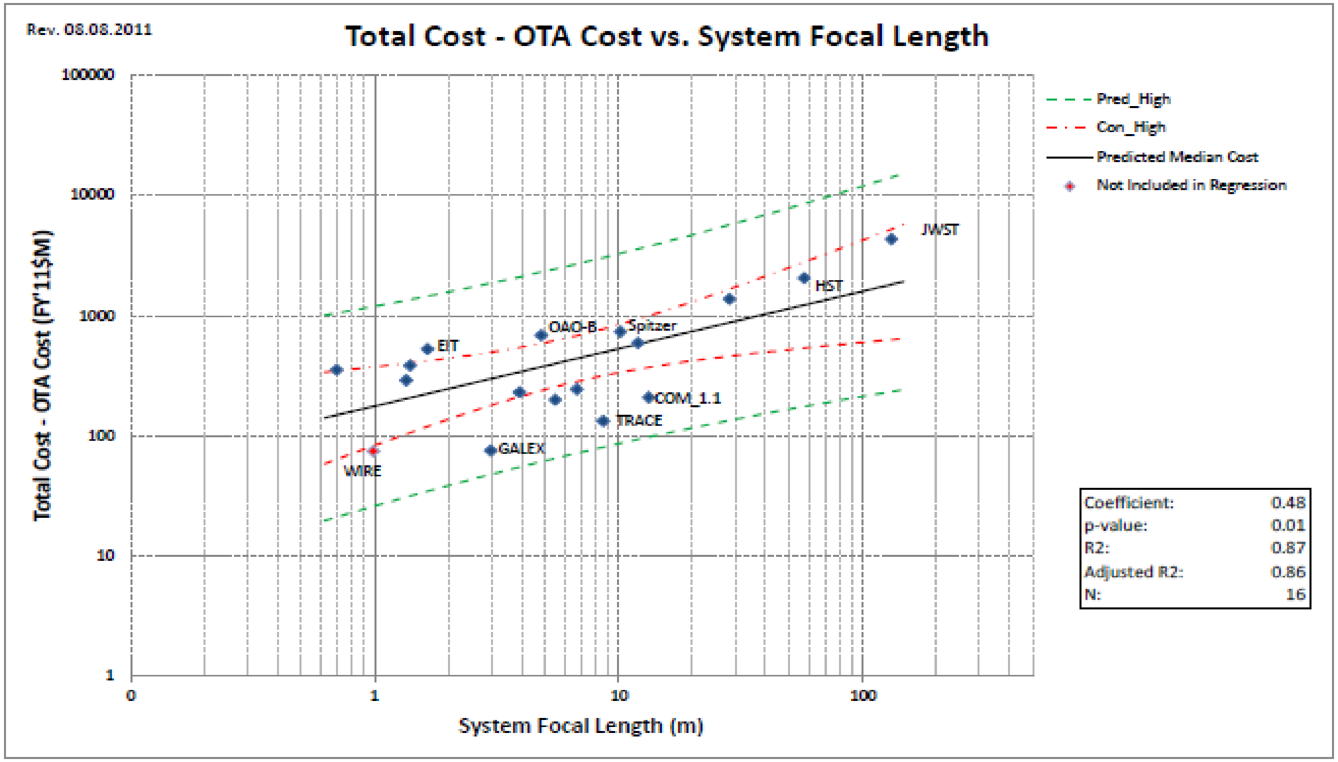
(Total – OTA) Cost ~ Dia $^{0.5}$ ***(N = 23; r^2 = 45%; SPE = 119%)***



(Total – OTA) Cost vs System Focal Length

Mission Cost increases with system focal length because FL indicates total Mission Volume and larger Payloads require larger spacecraft, power, communications, etc:

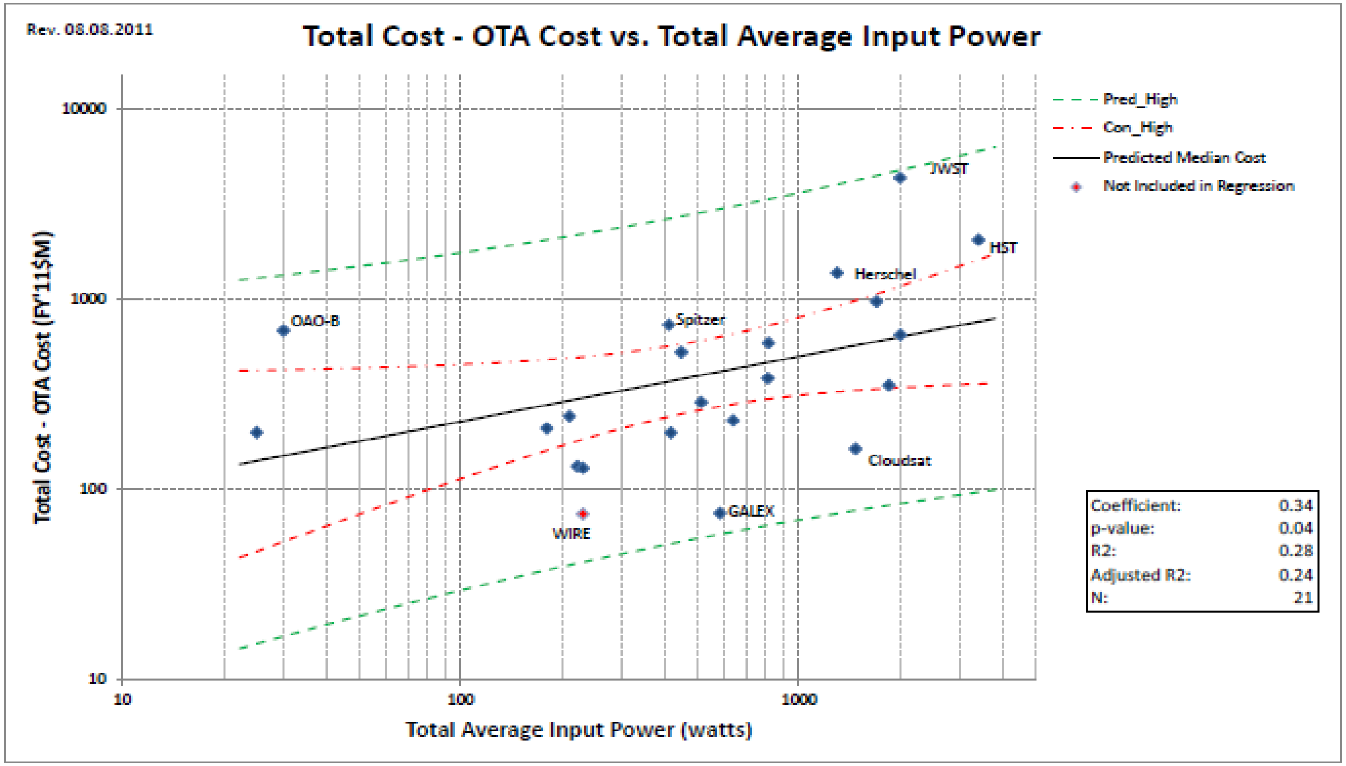
(Total – OTA) Cost ~ SFL $^{0.5}$ ***(N = 16; r^2 = 87%; SPE = 85%)***



(Total – OTA) Cost vs Power

Mission Cost increases with Average Power requirement:

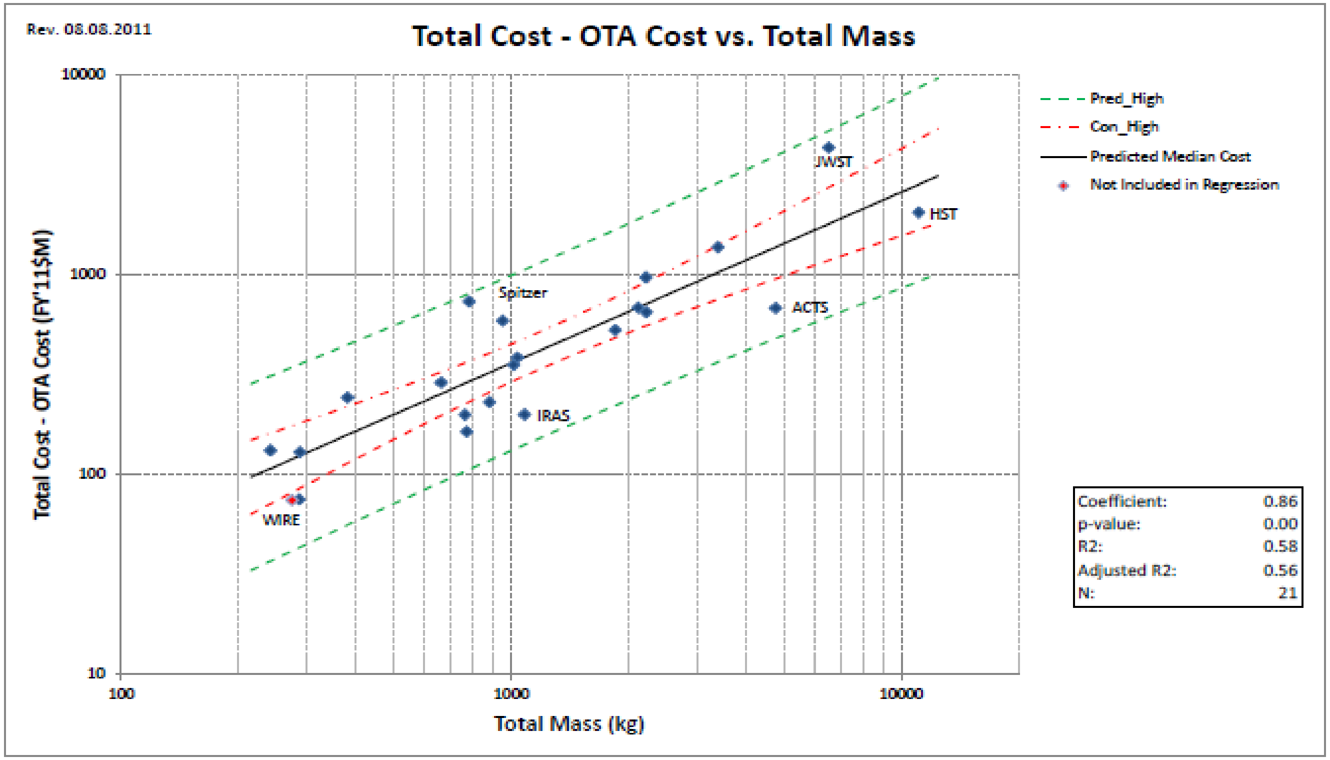
(Total – OTA) Cost ~ Power $^{0.3}$ ***(N = 23; r^2 = 28%; SPE = 173%)***



(Total – OTA) Cost vs Mass

Mission Cost increases with Mass because bigger missions are more expensive than smaller missions and bigger missions are more expensive than smaller missions:

(Total – OTA) Cost ~ Mass $^{0.9}$ *(N = 21; r^2 = 58%; SPE = 58%)*



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- **Conclusions**

Conclusions

Methodology developed for deriving parametric cost models based on engineering parameters using engineering judgment.

Validity of Cost models (this and historical) depend on database

Conclusions: Aperture

Consistent with Engineering Judgment Aperture Diameter is a good CER for OTA Cost:

OTA Cost ~ Diameter $^{1.4}$ ***(N = 15; r^2 = 82%; SPE = 123)***

1 variable only explains 82%, thus a 2 variable model is needed

Two variable model using Wavelength Diffraction Limit explains 98% of data variation with a low SPE.

OTA Cost ~ Dia$^{1.6}$ $\lambda^{-0.25}$ ***(N = 12, r^2 = 98%; SPE= 60%)***

In all cases, Areal Cost ($\$/m^2$) is less for larger telescopes

Testing the Model

Testing the Model

OTA Cost ~ Dia$^{1.6}$ $\lambda^{-0.25}$ ***(N = 12, r^2 = 98%; SPE= 60%)***

JWST to HST	Cost
2.7X Diameter	~5X
4X Wavelength	~0.7X
Total	~3.5X

HST OTA cost is approx \$0.47 B which implies a JWST OTA cost of approx \$1.6 B

- Current Actual is \$1.2B
- Final ???

Comparison with Historical Models

This study has identified a potential 3 variable model

$$\textbf{OTA Cost} \sim \mathbf{D}^{1.7}\ \lambda^{-0.3}\ \mathbf{T}^{-0.25}$$

Bely Model (corrected):

$$\textbf{OTA Cost} \sim \mathbf{D}^{1.6}\ \lambda^{-0.18}\ \mathbf{T}^{-0.2}\ \mathbf{e}^{-0.033(\mathrm{YOD} - 1960)}$$

Horak Model:

$$\textbf{OTA Cost} \sim \mathbf{D}^{0.7}\ \lambda^{-0.18}\ \mathbf{T}^{-0.2}\ \mathbf{e}^{-0.033(\mathrm{YOD} - 1960)}$$

But Horak had a different data base.

Three Variable Aperture Model

No three variable model yields a 'good' result, partly because we lack sufficient data.

Operating Temperature gives a statistically significant result

OTA Cost ~ $D^{1.7}$ $\lambda^{-0.3}$ $T^{-0.25}$ ***(N = 11, r^2 = 96%; SPE= 54%)***

More effort is required to understand issues related to:

- Design Life
- Year of Development

Space vs Ground

Coincidentally, the Space Telescope Model is similar to our previously published Ground Telescope Model:

$$\textbf{Space OTA Cost} \sim D^{1.6}\ \lambda^{-0.25}$$

$$\textbf{Ground OTA Cost} \sim D^{1.8}\ \lambda^{-0.5}\ e^{-0.04(YoD-1960)}$$

Conclusions: Mass

OTA mass is not a good CER

OTA mass is multi-collinear with diameter, and

more massive telescopes actually cost less to make.

For a given aperture diameter,

Free-Flying OTAs are ~2X more expensive per kg than Attached OTAs

Free-Flying OTAs are ~15X more expensive per kg than SOFIA

Free-Flying OTAs are 1000X more expensive per kg than Ground

Bottom line: using Mass as an OTA CER could easily lead one to make inappropriate programmatic decisions.

General Conclusions

Larger Diameter OTAs cost more than Smaller, but Larger Diameter OTAs actually cost less per square meter of Collecting Aperture.

Longer Wavelength OTAs cost less than Shorter.

Cryogenic OTAs may cost less than Ambient.

There appears to be a cost reduction with year, but requires more study.

If all parameters are held constant, adding mass reduces cost &

reducing mass increases cost.

BACKUP

Total Mission Cost Regression

Regressing on the 33 normal incidence, 'free-flying' UVOIR:

Total Mass is significant & has good R^2_{adj} and lowest SPE

Total Cost ~ Total Mass $^{1.1}$ ***(N = 31; r^2 = 74%; SPE = 93%)***

Diameter and System Focal Length which relates to 'Volume' are significant

Design Life is also significant

rev. 8.1.11	Total Cost vs V1																	
Variable Name	Aperture Diameter		System F Len.		FOV		Pointing Stability		Total Mass		Total Areal Density		Spectral Range minimum		Diff. Lim. λ		Operating Temp.	
Var. / p-value	0.89	0.00	0.59	0.01	0.13	0.52	-0.49	0.01	1.08	0.00	-0.39	0.00	0.06	0.26	-0.02	0.83	-0.15	0.54
Adjusted r^2	44%		84%		-4%		32%		74%		5%		-3%		-3%		-3%	
SPE	204%		142%		478%		159%		93%		345%		437%		374%		456%	
n	33		22		25		11		31		31		31		19		31	

Variable Name	Total Avg. Input Power		Data Rate		Design Life (exp)		TRL		Year of Dev. (exp)		Dev. Period (exp)		Date of Launch (exp)		Orbit	
Var. / p-value	0.74	0.00	0.02	0.80	0.01	0.06	-1.25	0.23	-0.02	0.45	0.03	0.00	0.00	0.87	0.12	0.02
Adjusted r^2	46%		-3%		67%		25%		-3%		69%		-2%		-1%	
SPE	378%		436%		167%		276%		365%		134%		329%		398%	
n	31		28		30		9		27		26		29		24	

(Total Mission – OTA) Cost Regression

Regressing on 13 'free-flying' UVOIR with Total & OTA cost data:

Total Mass is significant & has good R^2_{adj} and best SPE

(Total – OTA) Cost ~ Total Mass $^{1.1}$ ***(N = 12; r^2 = 82%; SPE = 60%)***

Diameter and System Focal Length which relates to 'Volume' are significant

Design Life which relates to 'Reliability' is significant

rev. 8.1.11		Total Cost - OTA Cost vs V1																
Variable Name		Aperture Diameter		System F Len.		FOV		Pointing Stability		Total Mass		Total Areal Density		Spectral Range minimum		Diff. Lim. λ		Operating Temp.
Var.	p-value	1.04	0.01	0.68	0.00	-0.26	0.33	-0.40	0.15	1.09	0.00	-0.32	0.36	-0.05	0.63	-0.03	0.86	-0.01	0.97
Adjusted r^2		63%		87%		20%		17%		82%		8%		-1%		-5%		-8%
SPE		103%		81%		171%		157%		60%		247%		257%		212%		290%
n		13		11		11		7		12		12		13		10		13

Variable Name		Total Avg. Input Power		Data Rate		Design Life (exp)		TRL		Year of Dev. (exp)		Dev. Period (exp)		Date of Launch (exp)		Orbit	
Var.	p-value	0.35	0.13	0.04	0.55	0.01	0.01	-1.09	0.58	-0.01	0.75	0.03	0.00	0.01	0.85	0.10	0.20
Adjusted r^2		38%		-6%		90%		-9%		-9%		58%		-8%		-9%	
SPE		170%		213%		108%		306%		275%		114%		285%		317%	
n		13		11		13		4		12		11		13		12	

Three Variable Aperture Model

Three variable model predictions

$$\textbf{OTA Cost} \sim \$100\text{M} \times D^{1.8}\ \lambda^{-0.25}\ e^{-0.03(YoD-1960))}$$

$$\textbf{OTA Cost} \sim \$100\text{M} \times D^{1.8}\ \lambda^{-0.3}\ e^{-0.02(YoD-1960))}$$

Based on only

Diameter JWST should cost ~6 more than HST

Wavelength JWST should cost ~1.5 less than HST

YOD JWST should cost ~2.5 less than HST

Complete Model predicts JWST should cost ~1.5 more than HST